Influence of different maintenance strategies on the availability of rolling stock

by

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DECLARATION

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ABSTRACT

The nature of maintenance in the rail environment is complex, particularly regarding the rolling stock. Maintenance influences the availability of rolling stock and is hence linked to customer satisfaction. This increases the need to implement an effective maintenance strategy if railroad transportation is to be a competitive mode of transport.

The research discusses different maintenance strategies that are used by different organisations. These are reactive maintenance, preventive maintenance and predictive maintenance. The main objectives of this research are to identify and describe different maintenance strategies, to ascertain the influence of these strategies on the availability of rolling stock and to identify and describe factors used in developing a maintenance implementation framework for rolling stock at the Passenger Rail Agency of South Africa (PRASA). Rail transport is a regulated environment. Rolling stock under a regulated environment has high demands made on it due to varying and complex requirements from both internal and external stakeholders, combined with changing political decisions. These demands make the rolling stock managers' decision-making process of managing the maintenance of rolling stock more difficult and complex.

Based on maintenance processes at PRASA, an extensive review was conducted of the maintenance literature from different environments, including the railway sector, and an implementation framework for a maintenance strategy has been developed. This is to make maintenance of rolling stock more proactive. In conducting the literature review, maintenance concepts were identified for the formulation of a maintenance strategy implementation framework.

The framework addresses business objectives, regulations, health, safety and environment demands and interaction between different maintenance tasks. The maintenance strategy implementation framework consists of different maintenance strategy categories, such as objectives, personnel, scheduling, data acquisition and analysis, materials requirements, maintenance programme and maintenance execution.

OPSOMMING

Die aard van onderhoud in die spoorwegomgewing, veral rollende voorraad, is ingewikkeld. Dit beïnvloed die beskikbaarheid van die voorraad, wat gepaardgaan met die kliënt se tevredenheid. Dit verhoog die behoefte om ‘n effektiewe onderhoudstrategie te implementeer wanneer die spoorwegvervoerbesigheid kompeterend gemaak word.

Die navorsing bespreek verskillende onderhoudstrategieë wat gebruik word deur verskillende organisasies. Dit is reaktiewe, voorkomende en voorspellende onderhoud. Die hoofdoelwitte van hierdie navorsing is om verskillende onderhoudstrategieë, hulle invloed op die beskikbaarheid van rollende voorraad, faktore van die skepping van ‘n rollende voorraad raamwerk vir die onderhoudstrategie van PRASA in ‘n gereguleerde omgewing, te identifiseer en beskryf. Rollende voorraad in ‘n gereguleerde omgewing het hoë aanvraag as gevolg van wisselende en ingewikkelde vereistes van interne sowel as eksterne belanghouers, tesame met veranderende politiese besluite. Hierdie aanvraag maak die rollende voorraadbestuurders se besluitnemingsproses (soos die bestuur van die onderhoud van die rollende voorraad en versekering van die beskikbaarheid daarvaan) moeiliker en meer kompleks. Die navorsing het gefokus op tegniese aspekte en interne belanghouers.

Gebaseer op onderhoudsprosesse by PRASA en ‘n uitgebreide hersiening van die onderhoudliteratuur van verskillende omgewings en ‘n wêreldwye spoorwegsektor, ‘n benadering (raamwerk) vir ‘n onderhoudstrategie is ontwikkel, om onderhoud van rollende voorraad ‘n meer proaktiewe benadering te maak. In die literatuurstudie is onderhoudstake en -aktiwiteite, doelwitte, kriteria om onderhoudaksies te kies en wanneer hulle uitgevoer moet word, geïdentifiseer vir die formulering van ‘n onderhoudstrategieraamwerk.

Die raamwerk het betrekking tot besigheidsdoelwitte, regulasies, gesondheid, veiligheid en omgewingsvereistes en interaksie tussen verskillende onderhoudstake. In die onderhoudstrategieraamwerk word moontlike fases van aktiwiteite, insluitende doelwitte, personeel, skedulering, data-insameling en -analise, materiaalvereistes, onderhoudprogram en -plan en die uitvoering van take en deurtydse verbetering van ‘n onderhoudproses, gegee.

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Chapter 1

INTRODUCTORY CHAPTER

1.1 INTRODUCTION

This chapter serves to introduce the research undertaken and the research approach. The chapter is divided into several sections which deal with different concepts. Firstly, the chapter gives the project's theoretical background and rationale, followed by the research problem section. The research problem then leads to the aim of undertaking the study, after which research questions and objectives are outlined. Thereafter, the research design and methodology overview are given, followed by the demarcation of the study's delimitations and limitations and the research contribution. The chapter concludes with the outline of the study.

1.2 PROJECT BACKGROUND AND RATIONALE

South Africa has public transport system peculiarities which are not encountered in First World countries. These include dominance of low-capacity vehicles, vehicle maintenance, inter-association rivalry, industry sustainability and fleet age profile, lack of adequate financial resources to fund operational subsidies, lack of timeous capital investments to replace rolling stock, lack of integrated transport planning and absence of a firm commitment to public transport (Walters, 2008).

In South Africa, public transport plays a significant role in enhancing urban mobility, reducing road congestion, and reducing effects on the environment through harmful emissions (Walters, 2008). The economic growth of the country over the past few years has led to an increase in car ownership and hence road congestion; for example, in Gauteng, the 40 km trip between Johannesburg and Pretoria in the morning peak can take up to two hours or more. A similar situation can be found in Cape Town and other metropolitan areas (Walters, 2008). Hence, it is wise for workers to avoid heavy reliance on public road transport if possible, as it can result in employees being late for work and students for school.

The choice of mode of transport is often based on affordability. In a 2003 survey, it was established that 83.1% of households in South Africa have an income of less than R6 000 (Walters, 2008). This was the group that was identified to be heavily reliant on public transport as they could not afford personal vehicles. The main problems of public transport as shown by half of the South African households surveyed was that public transport was not available or was too far away. A third of the households were concerned with safety from accidents and bad driver behaviour, particularly in taxi services. Twenty percent of the households had problems with the cost of transport (Department of Transport, 2005). In 2003, most work trips were undertaken by car 32%, taxis 25%, bus 9% and train 6%. The bus and train services, being the subsidised modes, have a national share of 37%. In comparing the dominance of the two (bus and train), this depended on the area (Department of Transport, 2005).

South Africa faces a multitude of challenges in public transport services such as affordability, availability and safety. Passenger Rail Agency of South Africa (PRASA) has a market share of over 13% and transports over 372 million people to places of employment and education on an annual basis. According to PRASA Corporate Plan, (2019/21) one of the values of the organisation is to provide services that meet or exceed customer satisfaction. In order to do so, the organisation has to ensure the availability of its trains is high. However, the current performance and service offering is at an all-time low (PRASA Corperate Plan, 2019/21). The service is poor, unreliable, unpredictable and unsafe, resulting in the decline in customer and stakeholder confidence in PRASA's ability to deliver its mandate.

Over past years, the performance of PRASA has declined significantly from 646 million passenger trips recorded in 2009 to 472 million by 2012 which translates to a 174 million (or 26,9%) drop in the number of passenger trips. Besides this significant reduction in passenger train trips, PRASA is struggling with train delays and cancellations. Table 1.1 shows some of the problems the organisation is currently facing as well as some of the root causes.

Table 1.1: Problems being faced by PRASA (adapted from PRASA Corporate Plan (2019))

Coaches out of service	1 827 coaches or 40% of the fleet not in service – 62% of this is in maintenance (own and contractors)
Train set shortage	Only 248 train sets provided per day against a requirement of 287. Of this, 56 % have short formations i.e. less than 12 coaches per train set
Train cancellations	10% of peak trains are cancelled. This is a loss of 2.6 million "seats" per month or 117 200 "seats" per day
Train delays	An average train has five possible types of delay, each of which results in different minutes of delay. By the end of the third quarter of the 2016/17 financial year, average train delays were as follows, 21 minutes (Western Cape), 31 minutes (KZN), and 45 minutes (Gauteng)

Infrastructure to train delays increased	Of around 20–21% of train delays, infrastructure is responsible for 6.8% or nearly a third of them (first 6 months of 2016/17). This is double the number of infrastructure train delays experienced in 2010/11 (3.3%)
Track quality index deterioration	Track condition as measured by Track Quality index is showing a deterioration across all regions, leading to increased speed restrictions for the safety of commuters
Train accidents	An increase in accidents and train fires – 2 major accidents 2015/16 and 2016/17
Increase in security incidents	Security incidents increased by 16% year-on-year and incidents involving passengers showed an increase of 53% year-on-year for the first 6 months of 2016/17
Loss of passengers	Metro rail lost a quarter or 73 million of its passengers in the first six months of 2016/17 against the same period in 2014/15
Main Line Passenger Service (MLPS) decline	MLPS lost 83% of the 3.4 million passengers it once transported in 2008/9 as a result of 73% service reduction

The main problem currently facing the organisation is fleet availability as the organisation is failing to meet its daily operational demand. More than half of the fleet is parked at the depots or with various service providers due to either mechanical breakdowns or accidents. The reduction in fleet availability has a huge negative influence on revenue, passengers and customer satisfaction.

According to the PRASA corporate plan 2019/21, there are inadequate funds to implement and execute an effective maintenance regime. This is supplemented by the fact that since the 2014/15 financial year, the organisation has been seeing a decline in revenue as a result of reduced passenger numbers due to reduced fleet available for operational requirements.

In light of the above, to reduce the decline in revenue, the organisation needs a well-defined plan that will improve service delivery and ultimately regain lost customers. To achieve that, the organisation needs to put much focus on improving availability and reliability of rolling stock and infrastructure. The aim is thus to be able to transport between 400 to 500 million passenger trips in 2020/21 with at least 291 train sets at full capacity; that is a configuration with 12 coaches and with a target of 88,1% on-time performance. The medium- to long-term objective is for rail operations to have 3 840 to 4 600 coaches in service and increase its on-time performance to above 90% and availability to over 95% to fulfil the current travel demand (Prasa cooperate plan, 2019/21).

Since the research used data from the Western Cape region, it is important to state the following;

1. The Western Cape needs a fleet of 88 trains to service an estimated 14,5 million passenger journeys per month with average punctuality of 78%. Train frequencies vary between 3 and 15 minutes depending on the corridor. However:

a. Around 56 train sets are in operation; that is 63,6% of the total demand

b. The Western Cape provides approximately 43,5% of the national target of passenger trips for 2020/21

2. According to PRASA Corporate Plan 2019/21, the Western Cape has an average train delay of 21 minutes

3. There are four routes, namely;

    a. Southern line – This line is from central Cape Town to the southern suburbs to Muizenberg, then along the edge of False Bay to Simon’s Town.

    b. Cape Flats line –This line runs from Cape Town to Maitland, then turns south through Athlone, rejoining the Southern Line at Heathfield and the service ends at Retreat.

    c. Central line – This line serves the south-east of the city centre. The train travels from Cape Town to Langa. It does so on two different routes, namely on the southern and eastern sides of Pinelands. When the train gets to Langa it can either go to Mitchells Plain to Khayelitsha or through Belhar to Bellville.

    d. Northern line – This line serves the suburbs of Cape Town and some outlying towns. Some trains travel along the old line from Cape Town to Bellville. On this line, some trains go through Salt River, Maitland, Goodwood and Parow, while others use the route through Century City. After Bellville, the train can either go to Kraaifontein and Paarl to Wellington via Kuils River and Stellenbosch to Muldersvlei, or via Kuils River and Somerset West to Strand.

4. As stated by the corporate plan 2020/21, the Western Cape has an internationally high share of rail transport (55% of public transport travel) which reflects its development and extensive rail network focused on the important city of Cape Town.

1.3 RESEARCH PROBLEM

The problem the Passenger Rail Agency of South Africa is facing is the continual decline of performance and service which is currently at an all-time low with services being poor, unreliable, unpredictable and unsafe. As a result, by 2012 passenger trips had reduced by more than 26% from recorded data in 2009 and a drop of 372 million trips by the end of 2016/17 financial year. This means that the organisation is losing a lot of revenue and this has also resulted in job losses.

One of the major root causes of the decline of train performance is fleet maintenance. Failure to maintain the fleet effectively has resulted in a sharp decrease in fleet availability. PRASA has more than half of its fleet parked due to maintenance. Therefore, there has been a significant decrease in fleet availability with Western Cape having only 56 out 88 train sets available for service. The reduction in fleet availability hurts revenue and customer satisfaction. Since the revenue is low, the organisation cannot afford to implement a cost-effective maintenance regime.

The PRASA corporate plan 2019/21 clearly distinguishes between unavailability caused by the refurbishment programme and vandalism, and that caused by maintenance. It states that 62% of coaches that are down are due to maintenance. Analysis of PRASA data from 2016 to 2019 in the Western Cape, focusing on downtime caused by maintenance resulted in Figure 1.1 being produced. The number of hours is a summation of the total number of hours spent on maintenance during the indicated year. Some of the maintenance tasks were executed simultaneously. The aim of analysing the data was to have a clear picture of the total number of hours spent on all maintenance tasks in a given period. Therefore, even if the tasks were performed simultaneously, they were treated individually, since maintenance execution had to be given to all the tasks and hours put into restoring the coaches to operational level.

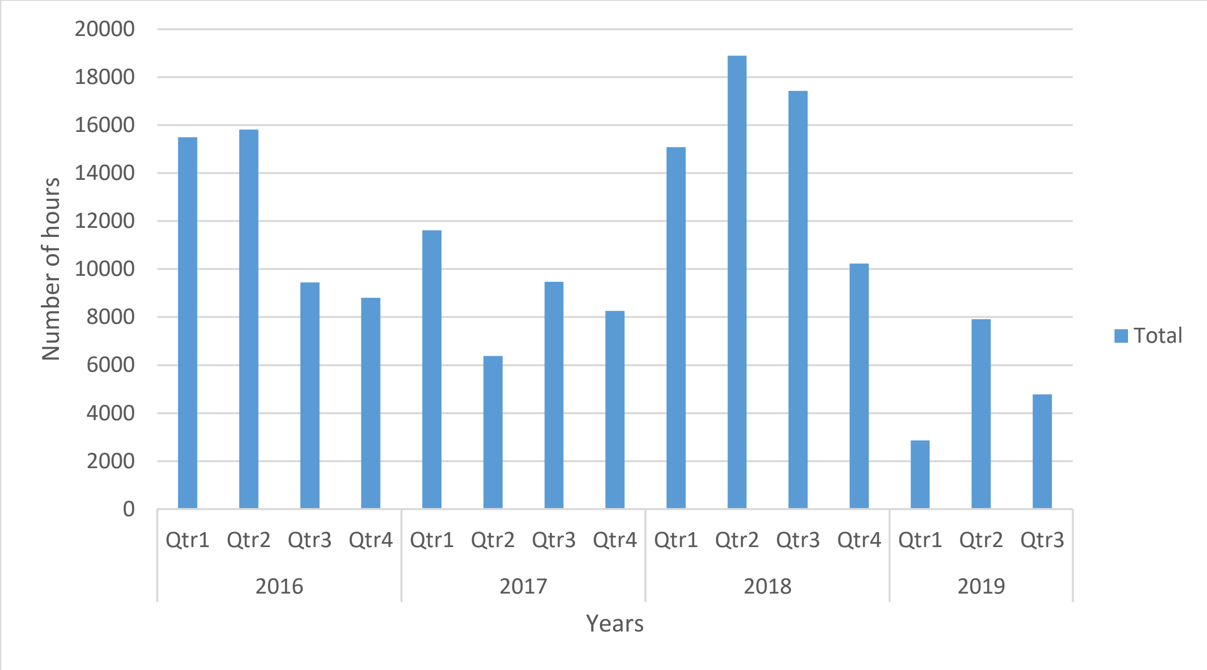

Figure 1.1: Summation of hours spent on maintenance

Therefore, the problem is that PRASA continues to experience a decrease in train availability with 62% of fleet unavailability being a result of poor maintenance.

1.4 AIM

The purpose of this study is to identify and describe factors influencing the development of a maintenance strategy for the maintenance of rolling stock since 62% of fleet unavailability is as a result of poor maintenance. The maintenance strategy is carried out to improve the availability of train sets. The influence of different maintenance strategies on the availability of rolling stock will be discovered. The research focuses mainly on the railway industry particularly the Passenger Rail Agency of South Africa (PRASA). This was done by analysing failure data through historical information. In analysing historical data, it is possible to identify components that are critical in ensuring the availability of rolling stock known as the 'mission-critical' components.

Conducting face-to-face interviews with the management at PRASA helped to validate the analysis of historical records. The interviews enabled the identification of components that are in the mission-critical components category. The railway industry should be able to use the information provided by this research to understand the impact of different maintenance strategies on the availability of rolling stock. The research will also give a framework that can be used to implement a maintenance strategy efficiently to improve the availability of rolling stock.

1.5 Research Questions And Objectives

The research problem led to the following research questions;

1. What factors need to be considered to develop a maintenance strategy implementation framework?
2. How can a maintenance strategy be implemented?
3. Which subsystems mostly affect rolling stock availability?
4. Which is the most suitable maintenance strategy to be implemented for rolling stock?

The main objective of this research is to unearth the influence of different maintenance strategies on the availability of rolling stock. The research objectives are;

1. To investigate the suitability of the use of different maintenance strategies on rolling stock.
2. To evaluate the influence of maintenance strategies on the availability of rolling stock.
3. To find concepts needed in implementing a maintenance strategy.
4. To select the most suitable maintenance strategy for rolling stock.
5. To develop a maintenance strategy implementation framework for rolling stock maintenance.
6. To verify and validate the implementation framework using subject matter experts (SMEs) validation interviews.

1.6 Research Design and Methodology

To be able to meet the stated research objectives, the research has been structured to follow a clear research design and methodology.

1.6.1 Research Design

The research type is both exploratory and descriptive. It is exploratory since it unearthed key issues and explored different maintenance strategies and maintenance concepts. It is descriptive in the sense that it described the implementation of each maintenance strategy considered.

The research is a mixed-method research design. This is because different research designs and data collection methods were used. The research design is a sequential exploratory mixed design. As explained by Creswell (2003), sequential mixed method design can start with a qualitative phase then followed by quantitative design. The qualitative phase is comparative whereas the quantitative is on the case study. The research designs used under mixed research design include;

a) Comparative – in this research, the comparison was done among different maintenance strategies and the influence of each maintenance strategy on the availability of rolling stock. This design was also descriptive as the description of different maintenance strategies, their impact on the availability of rolling stock was brought up.

b) Case Study – The research focused mainly on the Passenger Rail Agency of South Africa (PRASA). Much focus was on the Western Cape region; all the data analysed was from the Western Cape region.

1.6.2 Research Methodology

The research methodology was both empirical and non-empirical. It was empirical in the sense that in-depth interviews were conducted with PRASA employees such as production managers and technical supervisors on validating the proposed maintenance strategy implementation framework. It is also non-empirical in the sense that online information currently available was used in determining types of maintenance strategies, maintenance performance variables, maintenance strategy implementation and maintenance concepts.

The exploratory phase provided detailed information on the maintenance strategies, maintenance tasks as well as the influence of different maintenance strategies on the availability of rolling stock. The descriptive phase enabled maintenance strategies to be fully described. The comparative design was best in comparing the influences of different maintenance strategies on the availability of rolling stock. Figure 1.2 shows the research structure process which was followed in this thesis.

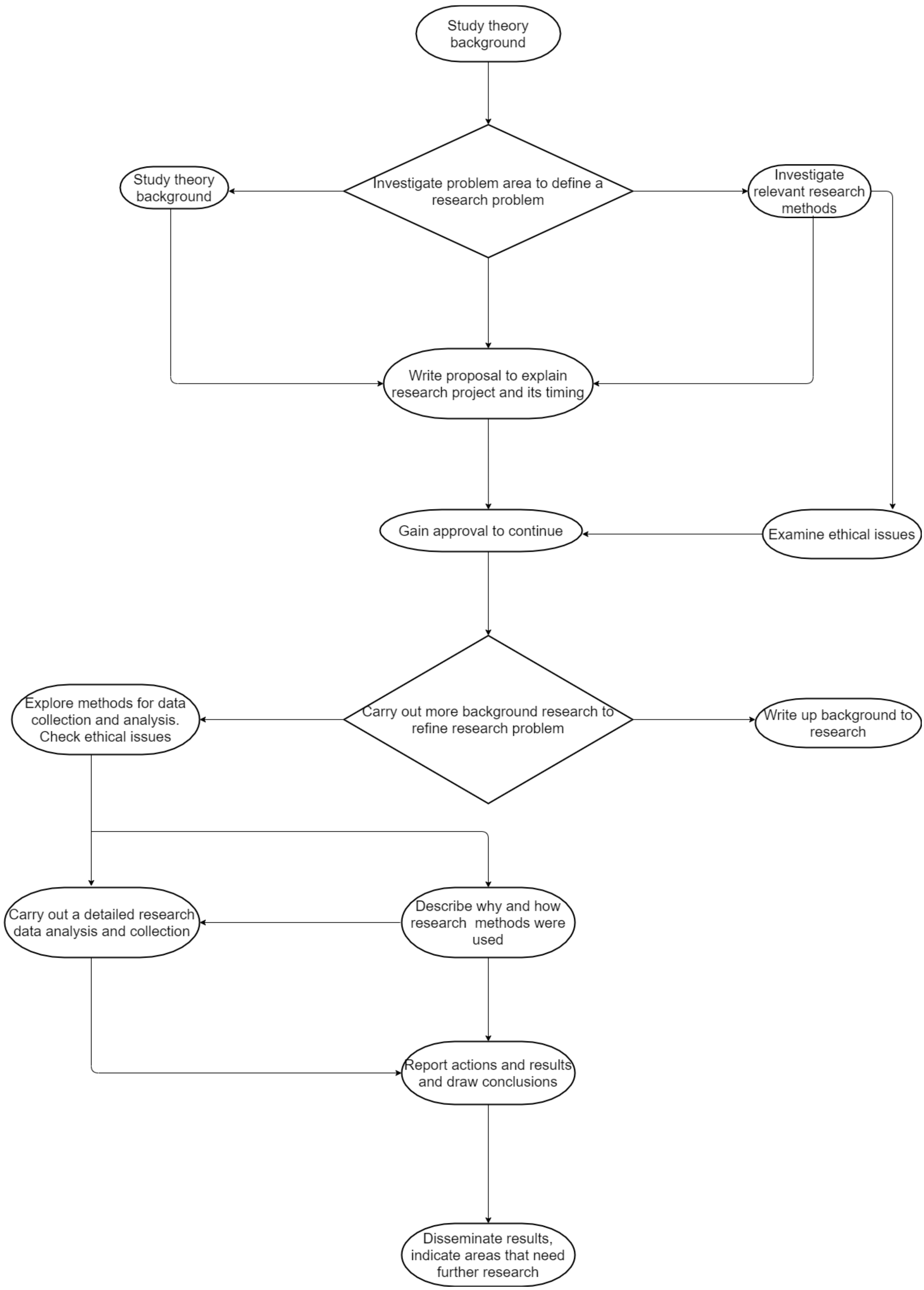

Figure 1.2: Typical research structure process (adapted from Emmert et.al. (1971))

1.7 DELIMITATIONS AND LIMITATIONS

The research is a case study research. It focused on PRASA in the Western Cape region, therefore the solutions provided apply to the dynamics of the Western Cape region, although some industries may find the results useful and implementable in their organisations.

Rolling stock availability at the PRASA (Western Cape) region is affected by several factors such as maintenance, refurbishment programme and vandalism. However, the research focused only on maintenance issues.

1.8 RESEARCH CONTRIBUTION

The research mainly benefited the railway sector. It can be used to implement a maintenance strategy. Adoption of the proposed implementation framework can increase the availability of rolling stock. The research also provided a detailed analysis of the influence of different maintenance strategies on the availability of rolling stock.

As a result of the research, the Passenger Rail Agency of South Africa will be able to;

a) Determine the influence of maintenance tasks on availability;

b) Evaluate the implementation of maintenance strategies;

c) Identify gaps for maintenance improvement;

d) Use the framework to implement a maintenance strategy;

e) Be able to optimise their maintenance strategies;

f) Be able to measure the performance of a maintenance strategy;

g) Identify other factors given by the research that may contribute to the effectiveness of a maintenance strategy.

1.9 RESEARCH TIMELINE

The document timeline provides the full outline of the research thesis. The schematic shown in Table 1.2 shows how much time was spent on each phase. It highlights only the most important headings of each section of the report.

Table 1.2: Project timeline

Tasks	Start Date	Duration (days)	End Date
Project Proposal	01 April 2019	45	15 May 2019
Literature Review	16 May 2019	70	25 July 2019
Research Design and Methodology	26 July 2019	50	10 September 2019
Correction of previous chapters	15 September 2019	30	15 October 2019
Data Collection	16 October 2019	45	30 November 2019
Data collection	10 January 2020	48	28 February 2020
Data Analysis	16 April 2020	46	31 May 2020
Framework Validation	01 June 2020	45	15 July 2020
Documentation	16 July 2020	60	15 August 2020

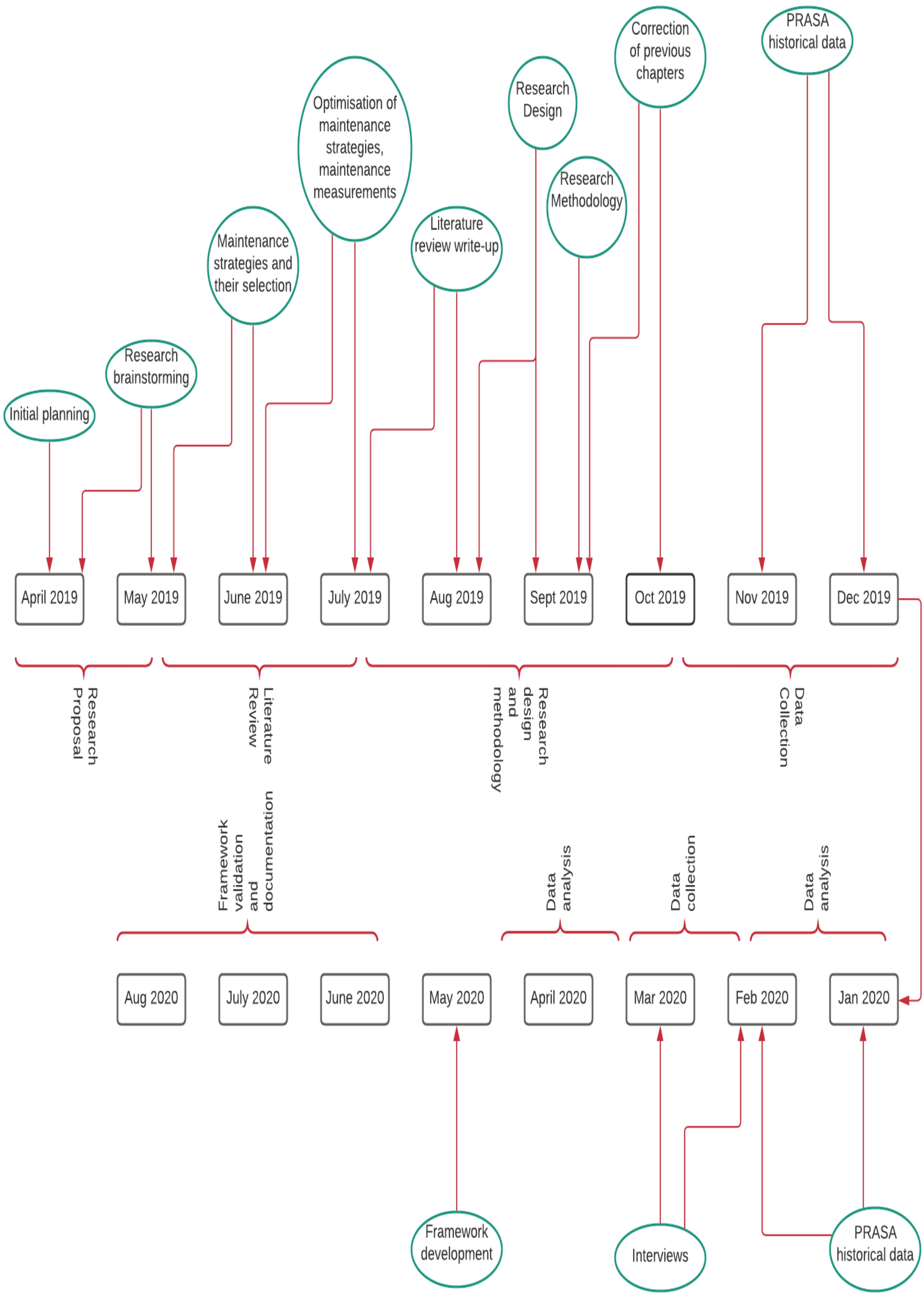

Figure 1.3: Research timeline

1.10 RESEARCH THESIS OUTLINE

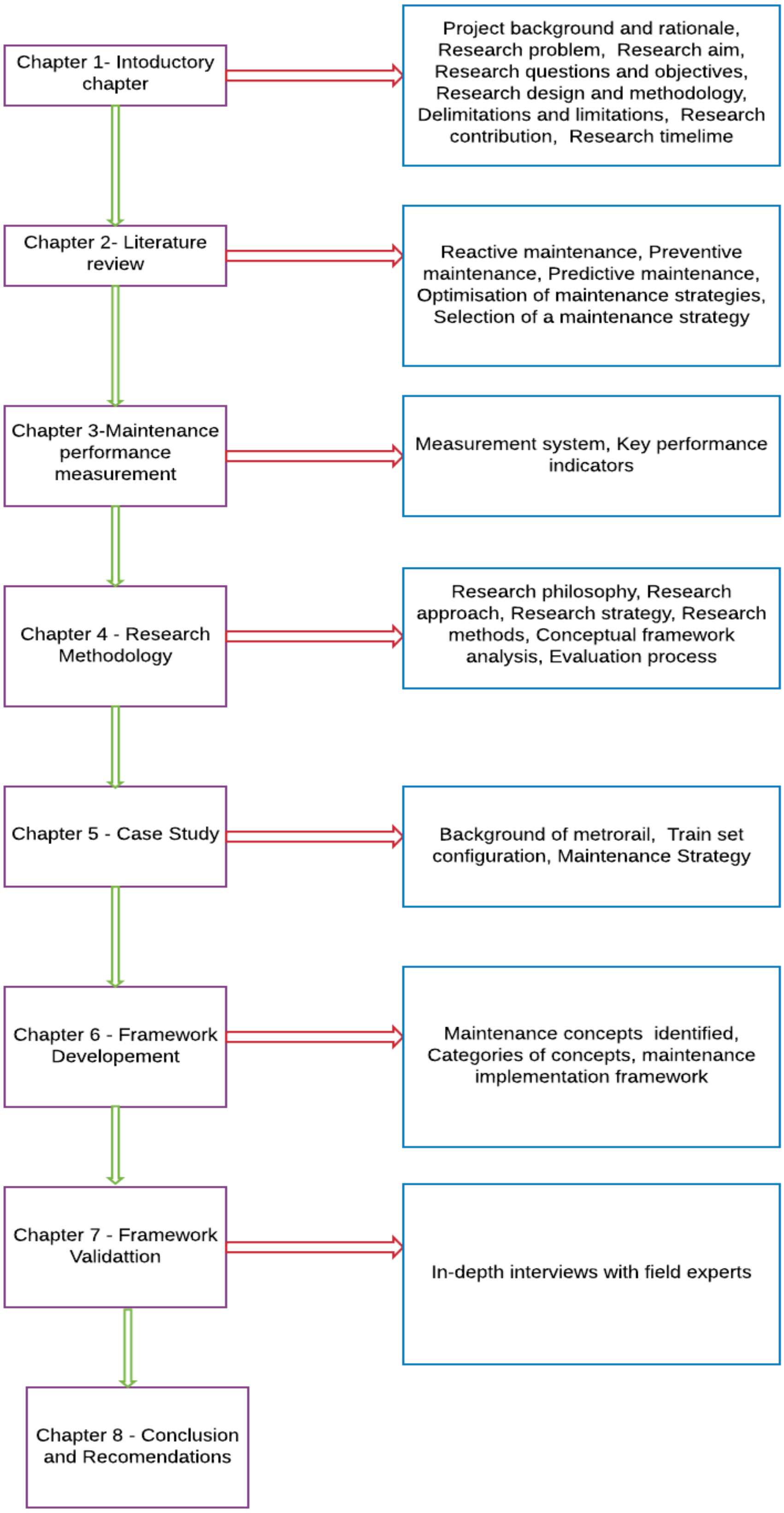

Figure 1.4: Research thesis outline

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Chapter 1 presented the research problem, background and objectives. This chapter focuses on the literature of maintenance as a whole, narrowing it down to maintenance techniques, strategies and methodologies. Furthermore, a literature analysis is done on the selection of maintenance strategies.

2.2 EQUIPMENT MAINTENANCE

Maintenance is a combination of technical, administrative and managerial actions taken during the life cycle of an item (Aju kumar, Gupta and Gandhi, 2019). This is done to return equipment to its working condition to enable it to perform all the functions it is intended for.

According to Rijsdijk and Tinga, (2016), thorough thinking has to be done to decide between maintaining equipment or not as shown in Figure 2.1.

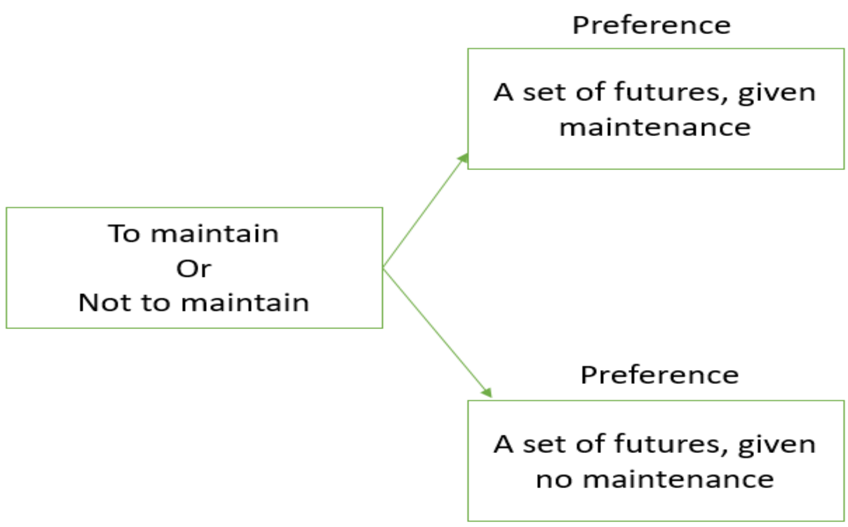

Figure 2.1: Maintenance decision tree (adapted from Rijsdijk and Tinga (2016))

Maintenance is important for ensuring the availability of an asset; it has a direct impact on both the costs and quality of products or services. Equipment failure not only results in a drop in productivity but also leads to the loss of timely services to customers and compromises on safety and environmental issues that damage the image of an organisation (Alabdulkarim, Ball and Tiwari, 2014a). The only way to eliminate maintenance costs is not to implement it at all; however, this brings about more costly consequences. Therefore most organisations opt to perform as little maintenance as possible as infrequently as possible, while ensuring that system availability and reliability are not compromised. Maintenance should be carried out when necessary to ensure continued availability of the system and reduction of costs associated with carrying out maintenance tasks (Horner, R.M.W.; EL-Haram, M A; Munns, 1997).

As stated previously, researchers have divided maintenance into different categories, including maintenance techniques, maintenance strategies and maintenance methodologies. However, depending on the definition used, researchers continue to differ on the elements that fall under each category. For this research, a maintenance technique is seen as a subtask of a maintenance strategy. This research views Total Productive Maintenance (TPM), Reliability-centred Maintenance (RCM), Risk-based Maintenance (RBM), and e-maintenance as maintenance methodologies. This is because they are used in selecting and/or implementing maintenance strategies. For example, under ‘planned maintenance’, which is the third pillar of TPM in the list below, a decision still needs to be taken on which maintenance strategy should be implemented (Nakajima, 1988; Rausand, 1998). The components of RCM consist of all the maintenance strategies. The strategy to be implemented is selected based on the seven RCM steps (Rausand, 1998; Afefy, 2010). In RBM, on the fourth module, one still has to decide which maintenance strategy to implement. Hence these are classified in this research as maintenance methodologies.

The methodologies are Total Productive Maintenance (TPM), Reliability-centred Maintenance (RCM), Risk-based Maintenance (RBM) and Business-centred Maintenance (BCM) among many others that researchers continue to propose. Each of these methodologies will now be discussed in more depth.

1. Total Productive Maintenance (TPM)

Total productive maintenance came as a result of a need for waste removal. The waste is normally due to operators, maintenance personnel and process, tooling problems and non-availability of components in time, idle machines and idle manpower, breakdown of machines and rejected parts (Nakajima, 1988; Carannante, 2002; Ohunakin and Leramo, 2012; Singh *et al.*, 2013). Zero-oriented concepts such as zero tolerance for waste, defects, breakdown and zero accidents are becoming a prerequisite in the manufacturing and assembly industry (Singh *et al.*, 2013). The goal of a TPM programme is to improve productivity and quality along with increased employee morale and job satisfaction. TPM is an innovative approach to maintenance that optimises equipment effectiveness, eliminates breakdowns, and promotes autonomous operator maintenance through day-to-day activities involving the total workforce (Nakajima, 1988; Carannante, 2002; Ohunakin and Leramo, 2012; Singh *et al.*, 2013). It consists of seven pillars, namely:

a. Autonomous maintenance – This pillar is based on the concept that if operators take care of small maintenance tasks, it will free up skilled maintenance people to concentrate on more value-added activity and technical repairs. The operators are responsible for checking and carrying out minor servicing of their equipment on a daily basis to prevent it from deteriorating. By the use of this pillar, the aim is to maintain the machine in new condition. The activities involved are cleaning, lubricating, visual inspection, tightening of loosened bolts, etc. (S.Nakajima, 1988; Ohunakin and Leramo, 2012; Singh *et al.*, 2013).
b. Focused maintenance – Under focused maintenance, certain activities are performed, including some that are developed by inter-functional teams and some by individuals. Their goal is to maximise the effectivity of the equipment and decrease the company's losses and waste.
c. Planned maintenance – It aims to have trouble-free machines and equipment without any breakdowns and to produce components meeting the specified quality level, giving total customer satisfaction. Maintenance can be carried out as Preventive Maintenance, Breakdown Maintenance, Corrective Maintenance or Maintenance Prevention. Planned Maintenance is a proactive approach which uses trained maintenance staff to help train the operators to better maintain their equipment. The objective of Planned Maintenance is to achieve and sustain the availability of machines at optimum maintenance cost, improve reliability and maintainability of machines, with zero equipment failure and breakdown and ensure the availability of spares at all times (S.Nakajima, 1988; Singh *et al.*, 2013).
d. Quality maintenance – This is geared towards achieving customer satisfaction through delivery of the highest quality product. Through focused improvement, defects are eliminated from the process after identifying the parameter of the machine which is affecting the product quality (Nakajima, 1988; Singh *et al.*, 2013).
e. Education and training – Continuous improvement is possible only through continuous improvement in knowledge and skills of the people at different levels (Nakajima, 1988; Singh *et al.*, 2013).
f. Safety, health and environment – The purpose of this pillar is to create a safe workplace and a surrounding area that is not damaged by the processes or procedures of the organisation.

Utmost importance is given to Safety in the plant. The objectives of this pillar are to achieve zero accidents, zero health damage and zero fires (Nakajima, 1988; Singh *et al.*, 2013).

g. Office TPM – Office TPM is the pillar which follows the other four pillars of TPM (JH, Kaizen, QM and PM). Office TPM must be practised to improve the productivity and efficiency of the administrative functions. This includes analysing processes and procedures which can be automated. Office TPM addresses nine major losses, which are: processing loss, cost loss including in areas such as procurement, accounts, marketing, sales leading to high inventories, communication loss, idle loss, set-up loss, accuracy loss, office equipment breakdown, communication channel breakdown, telephone and fax lines and time spent on retrieval of information (Nakajima, 1988; Singh *et al.*, 2013).

However, Singh *et al.* (2013) proposed an eighth pillar which is “Development Management”. The TPM concept is implemented in a phased manner in the machine shop of a company manufacturing automotive components. In each phase, one TPM pillar is implemented. Overall equipment effectiveness (OEE) is taken as a measure of success of TPM implementation.

2. Reliability-centred Maintenance (RCM)

Reliability-centred Maintenance is used to improve the availability of plant components and to reduce downtime. It helps in identifying the maintenance requirements of a plant. The methodology uses more than one maintenance strategy depending on the plant maintenance requirements (Afefy, 2010).

The methodology uses preventive maintenance, predictive maintenance, real-time monitoring, run-to-failure and proactive techniques. These are integrated to ensure both availability and reliability of plant components (Afefy, 2010). According to Rausand (1998), RCM has steps that it follows;

a. System selection and data collection

b. System boundary definition

c. System description and functional block

d. System function functional failures

e. Failure mode effect analysis

f. Logic tree diagram

g. Task selection

The factors affecting the selection of critical systems in RCM are mean time between failures, total maintenance cost, mean time to repair and availability (Afefy, 2010). Figure 2.2: shows the components of the RCM programme.

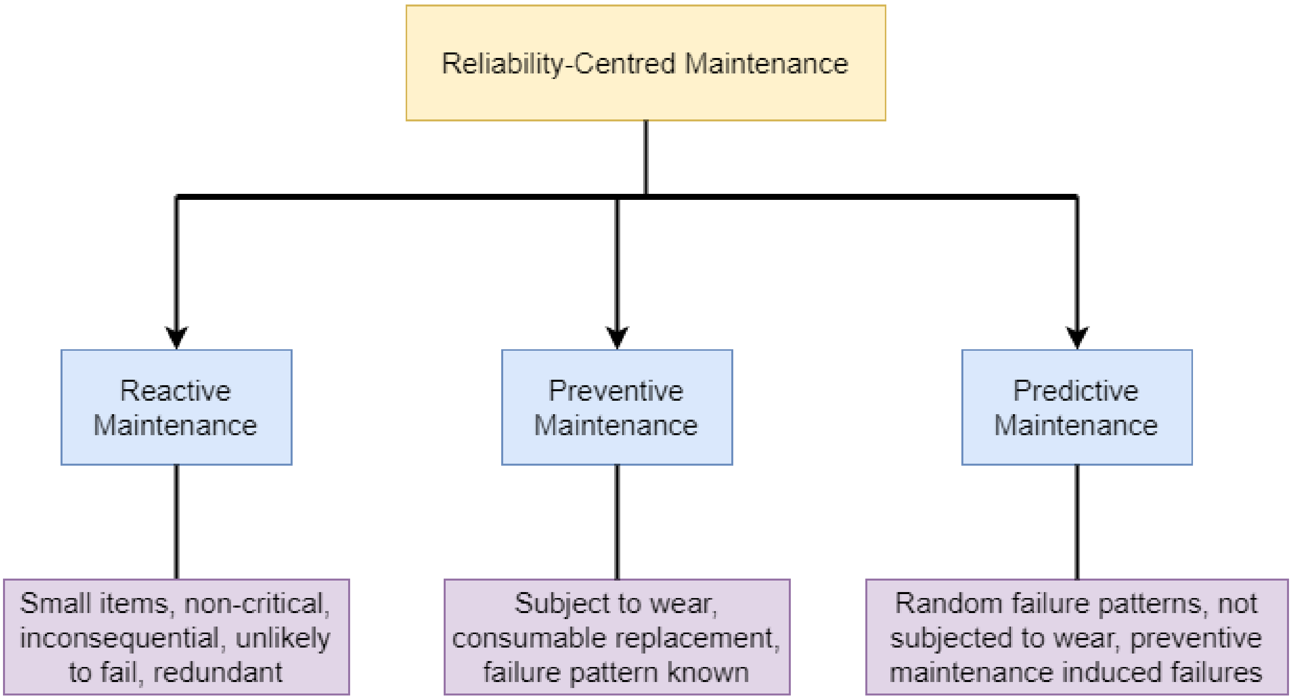

Figure 2.2: Components of the RCM programme (adopted from Afefy (2010))

3. Risk-based Maintenance (RBM)

Organisations often find themselves having a problem selecting the best maintenance strategy to implement. Normally, the choice of a maintenance strategy depends heavily on the organisation's resources such as spare parts, personnel and objectives. Risk-based maintenance offers the organisation a better option of reducing maintenance costs whilst meeting their objectives. According to Krishnasamy, Khan, and Haddara (2005), it enables maintenance engineers to come up with a maintenance strategy to minimise the risk that can cause breakdowns or system failures. Equipment failure has always affected the production system through reduced production capability, resulting in high operational costs as well as poor customer service (Arunraj and Maiti, 2007). Engineers often have problems in implementing a maintenance strategy that will keep the equipment running, which does not deviate from measurements, is environmentally friendly, which does not increase operational costs and which ensures safety to maintenance personnel and equipment users (Arunraj and Maiti, 2007). Risk-based maintenance, according to Krishnasamy, Khan, and Haddara (2005) consists of four modules, namely:

a. Identification of the scope

The whole plant is assessed by breaking it down into systems. The systems are then divided into a subsystem, then broken down into different components. Information that will be necessary for carrying out the analysis is accessed as well as the failure modes that can be expected (Krishnasamy, Khan and Haddara, 2005).

b. Risk assessment

The major consequences as a result of identified potential failures are analysed. At this stage, a fault tree analysis is used. The failure data is used at this stage to calculate the probability of failure and a consequence analysis is used to quantify its effect (Krishnasamy, Khan and Haddara, 2005). Researchers such as Arunraj and Maiti (2007) and Krishnasamy, Khan, and Haddara (2005) indicate that there are three risk assessment approaches. These are qualitative, quantitative and semi-quantitative.

c. Risk evaluation

At this stage, the risk level is determined. All components that have risks higher than the threshold are used to determine the maintenance strategy to be implemented (Krishnasamy, Khan and Haddara, 2005).

d. Maintenance planning

According to Krishnasamy, Khan, and Haddara (2005), a maintenance plan is developed from the components that have a high risk. The frequency of maintenance can also be developed from the frequency of failure.

Figure 2.3 shows a summary of the risk-based maintenance steps. The steps are identification of the scope, risk assessment, risk evaluation and maintenance planning.

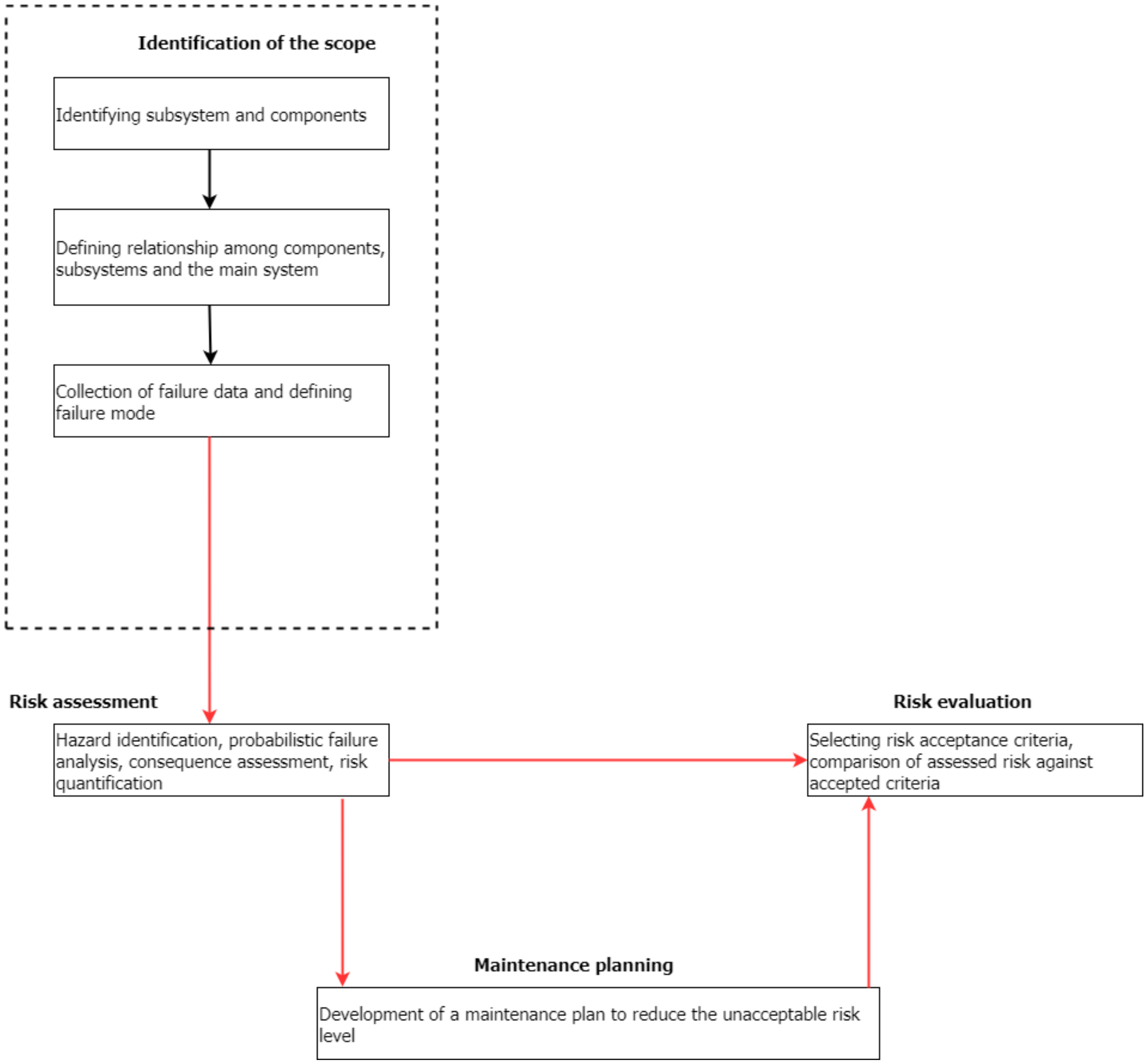

Figure 2.3: Architecture of RBM methodology (adapted from Krishnasamy et.al (2005))

2.3 MAINTENANCE STRATEGIES

According to Patidar L, Soni VK and Soni PK (2017), a maintenance strategy is a structured upkeep of equipment. It involves identification, researching and execution of repairs, replacing and inspection decisions and formulating the best life plan for each section of the plant in coordination with other departments.

According to Eti, Ogaji and Probert, (2006) when an organisation wants to develop and implement a maintenance strategy it has to go through three steps, namely;

1. Work identification. The organisation has to come up with a list of what needs to be done to each system, subsystem or component.

2. Purchase all the necessary resources. The resources may include spare parts, skilled personnel, and tools to use. These are necessary for implementing the proposed plan.

3. Strategy implementation. The resources must be managed properly.

Mishra *et al.* (2015a) added that implementation of any maintenance strategy is often difficult due to an organisation failing to adopt a systematic and consistent implementation methodology. Organisations cannot adopt a methodology from other organisations as their set-up, objectives, personnel, and availability of resources may be different.

Several maintenance strategies have been proposed by researchers. However, their applicability varies from organisation to organisation. The maintenance strategy depends on the organisation, maintenance resources, and skills available. Maintenance is, however, a collective responsibility and those tasked with it should be supported with all the resources required (Organ *et al.*, 1997). According to Phogat and Gupta, (2017), maintenance strategies have different types of tasks which include actions (inspections, replacement, repairing), procedures and time. The most common maintenance strategies as mentioned by Nazeri and Naderikia (2017) among many other researchers are;

1. Reactive maintenance

2. Preventive maintenance

3. Predictive maintenance

Figure 2.4 shows the three most common maintenance strategies mentioned above.

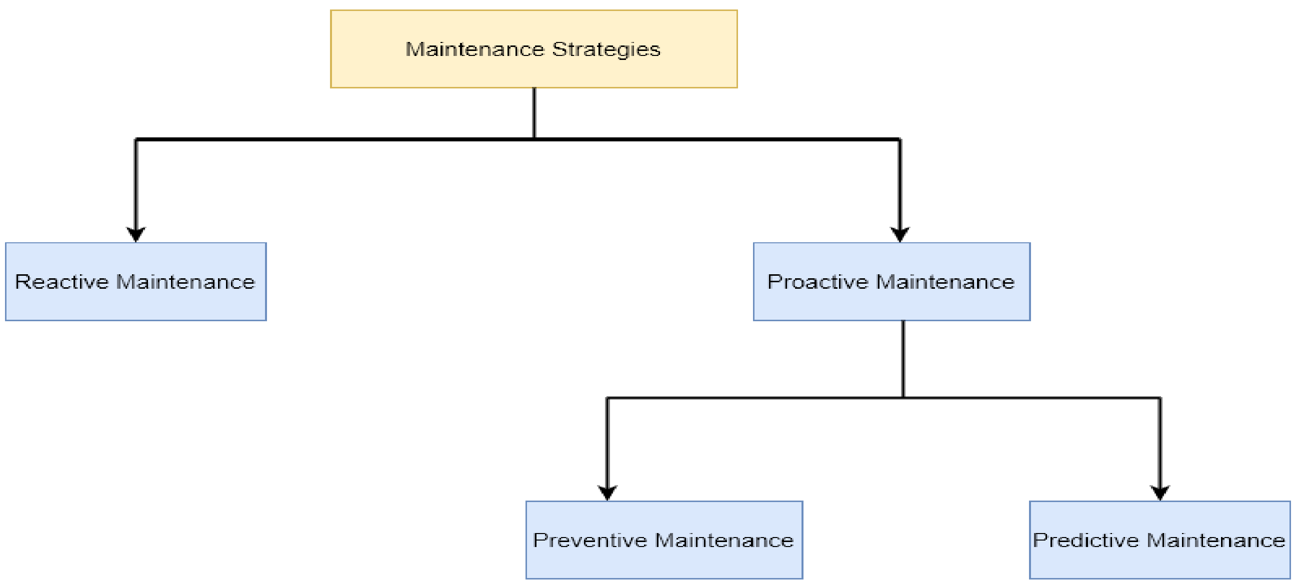

Figure 2.4: Maintenance approaches (adapted from Alabdulkarim, Ball and Tiwari (2014a))

A maintenance strategy is made up of one or more maintenance techniques (also called maintenance types). According to Vlok PJ, (2011), maintenance strategies and maintenance techniques are sometimes used interchangeably. However, in this research, a maintenance technique is taken as a subtask of a maintenance strategy. Thus, a maintenance strategy is taken as the ultimate direction an organisation follows. It consists of one or more maintenance techniques.

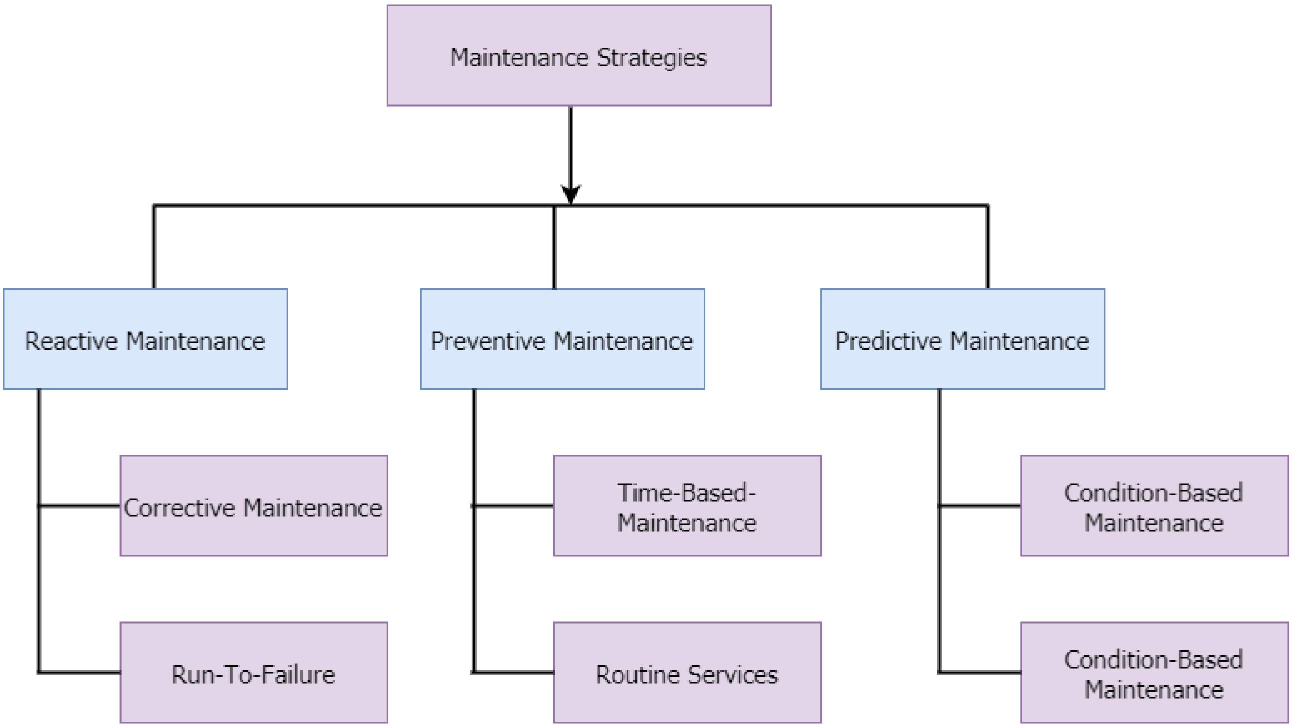

Figure 2.5: Maintenance strategy tree (adapted from Vlok PJ (2011); Tiwari et al (2014a))

A maintenance strategy is formulated or implemented so that the organisation can keep its system running. However, there are other secondary objectives such as caring for the environment in cases where unmaintained equipment poses a threat to the environment, possibly due to high noise levels as well as the quality of products. To optimise maintenance, Jonsson (1997), proposed a maintenance management framework that effectively focused on all factors which affect the success of a maintenance strategy. These factors which Jonsson (1997) referred to as maintenance management components are;

1. Goals and strategy: The maintenance strategy should be in line with the business objective of the organisation. Prioritising maintenance will help in meeting the business objectives. The strategy should be written down and be known by everyone. The management should also support the maintenance strategy being implemented.

2. Human aspects: In the research done by Thilander in 1992, it was found out that competence, information, and motivation were key in job satisfaction, increase in productivity and effective

maintenance. In the research, it was established that the lack of commitment from the foreman and senior management resulted in several breakdowns.

3. Support mechanisms: These help in making communication and flow of information easy. They form a feedback loop that is necessary for reviewing the maintenance strategies being implemented.

4. Tools and techniques: These help in implementing a maintenance strategy effectively and efficiently. Having the right tools makes maintenance work easy to execute. Adopting the right techniques helps in maintaining equipment not only 'to working condition' but 'to good as new condition' as well.

5. Organisation: Maintenance personnel should be organised into teams. Maintenance tasks should be assigned to different teams based on their size, expertise and competence.

Several factors need to be put in place to implement an effective maintenance strategy. Crespo Marquez and Gupta (2006) suggested that inventory and procurement, work order system, computerised maintenance management systems, technical and interpersonal training and human resources (formation of maintenance groups) should not be neglected in formulating and implementing a maintenance strategy.

When analysing maintenance strategies, Dhillon (2010), concluded that their effectiveness is greatly reduced by human error. Human errors found in maintenance were classified in terms of operating errors, assembly errors, design errors, inspection errors and maintenance errors.

The proper implementation depends on the maintenance personnel. Those in the maintenance department can decide to use the wrong tools, or wrong methods of implementation due to several factors. This, in turn, tends to negatively affect the reliability of equipment (Cromie *et al.*, 2015). In the research done by Cromie *et al.* (2015) focusing on the lobby activities, conclude by advocating for the creation of maintenance teams to improve the effectiveness of a maintenance strategy.

Human beings play a central role in the effectiveness of a maintenance strategy. According to De Felice and Petrillo (2011), several factors cause people to perform duties wrongly especially in maintenance. Some of the factors are;

1. Humans are often quite reluctant to admit mistakes. Instead of a maintenance task being reworked, it is carried out with an error leading to a compromise in the availability of the system.

2. Humans often overlook or misread written instructions.

3. Most people fail to recheck specified procedures for mistakes.
4. Humans frequently respond irrationally in emergencies.
5. Humans normally carry out tasks while thinking about other things.
6. Humans are normally poor estimators of clearance, distance, and speed.
7. A significant proportion of humans become quite complacent after successfully handling hazardous or dangerous items over a long period.
8. People often use their hands first to test or explore.
9. People get easily confused with unfamiliar things.
10. Generally, people regard manufactured items as being safe.
11. Usually, humans tend to hurry at one time or another.

In another research study done by Morant, Larsson-Kråik, and Kumar (2016) on the railway signalling system, it was found that one of the main reasons for the ineffectiveness of maintenance strategies was due to the errors from humans in carrying out maintenance.

In a railway setup, proper maintenance helps to achieve reliability, safety, and availability. Scheduling maintenance at the right time eliminates unnecessary downtime (Rezvanizaniani, Barabady, and Kumar, 2009). Also, to achieve better results from a maintenance strategy, a close relationship is required between management, maintenance personnel and analysts (Vatn, Hokstad and Bodsberg, 1996). According to Argyropoulou, Iliopoulou, and Kepaptsoglou (2018) in a railway setup, maintenance success depends on resources, scheduling, and implementation.

In light of the discussed merits of properly implementing a maintenance strategy, it is very difficult or often even impossible for organisations to implement the same maintenance strategy as this is largely influenced by the type of system the organisation has. Different factors that come into play are resources, human resource and business objectives (Mishra *et al.*, 2015b). An effective maintenance strategy for their rolling stock is a top priority for different rail organisations. Researchers have proposed various maintenance strategies and the rail organisations have implemented a number of them; however, organisations do not implement the same strategy as it is dependent on other factors such as finances (Rezvanizaniani *et al.*, 2008).

In analysing each maintenance strategy, the focus is on factors that affect their positive influence as has been highlighted in the above discussion. The factors used in the analysis are maintenance tasks/ actions, maintenance strategy components and time of implementing maintenance among others.

Mishra *et al.* (2015a) refer to the above factors as maintenance functions where the list of these functions includes spare parts management, inventory, procurement and operational involvement. Information and being cognisance of these factors may help an organisation improve the effectiveness of its maintenance strategy and the performance of the organisation.

Maintenance normally follows a fairly predetermined procedure as shown in Figure 2.6.

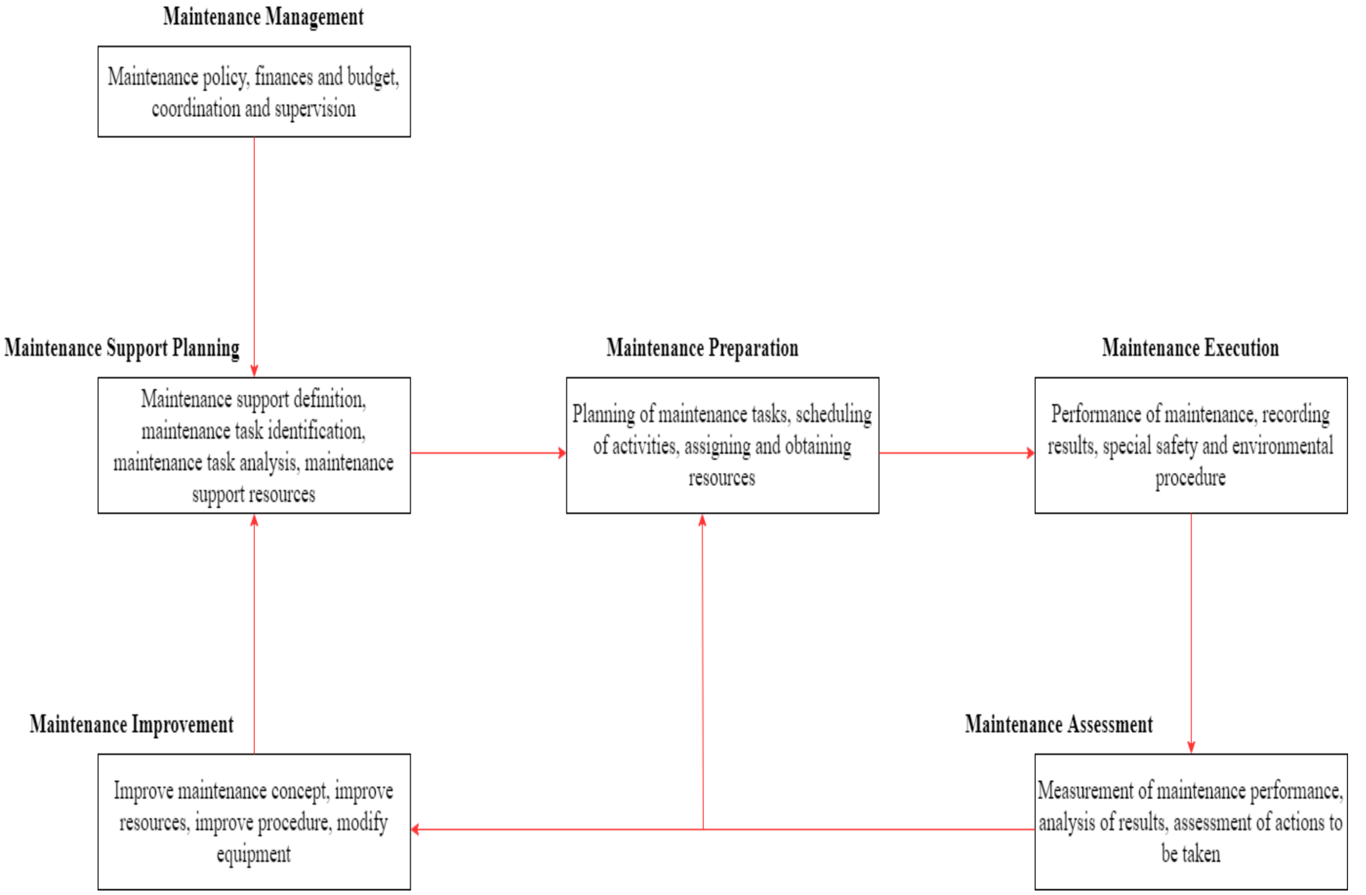

Figure 2.6: Maintenance processes (adapted from Morant et. al. (2016))

The maintenance strategies in the following sections are analysed in terms of key aspects that stand out in most of the research studies. These include maintenance scheduling, maintenance execution, data collection, management commitment, resource availability, level of skill and some others depending on the strategy being discussed. This does not in any way mean the other aspects are less important as they will also be mentioned in section 6.1. However, some of the aspects which easily can be discussed in a group such as repairing, replacing and lubricating are also handled under the heading of execution.

2.3.1 Reactive maintenance

This maintenance strategy encompasses corrective maintenance and run-to-failure maintenance techniques as shown in Figure 2.5. With this type of maintenance strategy, systems, subsystems or components are allowed to run until they fail. Maintenance activities are conducted when these stop functioning. It is the oldest type of maintenance strategy (Bengtsson, 2014). This strategy enables the organisation to keep the number of required maintenance personnel low. Repairs are only carried out on failed components and normally only to a sufficient extent to return them to operation level. Reactive maintenance strategy reduces maintenance costs; however, the major disadvantage is its failure to predict breakdowns and at times replacing machinery instead of repairing it (Laura, 2001).

Reactive maintenance is adopted in the railway industry when an unforeseen failure takes place. It is, however, the least preffered maintenance strategy in the railway sector. Reactive maintenance is implemented when applying preventive maintenance is difficult or expensive and failure consequences are insignificant (Organ *et al.*, 1997; Selcuk, 2017). As a result, components are allowed to run up to failure.

2.3.1.1 Scheduling

Scheduling of reactive maintenance is done when there is failure. Maintenance is only carried out when there is a breakdown, otherwise the system continues to run. In rolling stock, it can be carried out when trains fail.

2.3.1.2 Implementation

In a study of the railway signalling system, several alternatives were stated for consideration if the system fails. These are part of reactive maintenance. They can be summarised as follows from the findings of Morant, Larsson-Kråik, and Kumar (2016);

1. The component that has broken down can either be repaired or replaced.
2. Check if the failure is not due to software; if it is, restart the program or upgrade the software version.
3. Fix the component to working condition; however, schedule maintenance to return the component to as good as new status.
4. Carry out adjustments and lubrication on component connections.
5. Control the system to prevent further problems emanating from the current breakdown.

1) Resources availability

Maintenance personnel should focus on what is needed and when it is needed. However, it is sometimes very difficult to manage both. To minimise the effects of reactive maintenance, resources such as spare parts, tools and maintenance personnel should always be on standby (Organ *et al.*, 1997). This falls under the run-to-failure maintenance technique.

Sometimes in reactive maintenance strategy, the solution can be the replacement of the failed component rather than repairing it. This might be due to the component having exceeded its useful life. At this stage, repairing becomes costly as it will continue to fail unexpectedly and frequently.

2) Level of skill

According to Organ *et al.* (1997), research has shown over the years that the future of organisations depends on people, not on technology or computer systems. The effectiveness of a team is much greater than the combined efforts of individuals. Shared responsibility for duties is fundamental in executing maintenance activities efficiently and effectively. The success is measured by achieving a commonly agreed objective rather than by individual accomplishments (Organ *et al.*, 1997).

Maintenance personnel working in a reactive maintenance strategy must be well-versed in repairing components as well as replacing a component in a system. These tasks should be carried within a short space of time to reduce downtime. It therefore calls for competent personnel.

3) Management Commitment

Management should ensure that all resources needed to carry out maintenance activities are always available. These may include maintenance personnel, tools and spare parts among other things (Organ *et al.*, 1997).

2.3.1.3 Failure rate

Failure is marked by a point when the system or component is no longer able to perform or run according to its design objective (Vilarinho, Lopes and Oliveira, 2017). Normally, after failure, one determines and documents the effects of the failure, failure mode, and its causes and ultimately how frequently or regularly it happens (failure rate).

Failure rate helps to predetermine when to expect the next failure and thus to pre-plan on maintenance tasks. In reactive maintenance, normally failure rate only helps the maintenance personnel to ensure that all resources such as spare parts and personnel are available at the expected time of failure. This helps to reduce downtime.

2.3.1.4 Summary of reactive maintenance strategy

Reactive maintenance can be costly due to the following;

1. Great consequences as a result of system/subsystem/component failure.
2. Unexpected failures can be at a time when maintenance personnel or spare parts are not available. This will result in more downtime (Horner, R.M.W.; EL-Haram, M A; Munns, 1997).

However, reactive maintenance is a better strategy when;

1. The consequences of failure are less.
2. It is difficult to monitor the condition of different components that form the system.
3. The cost of applying reactive maintenance is far less than that of applying proactive maintenance strategy (Horner, R.M.W.; EL-Haram, M A; Munns, 1997).

2.3.2 Preventive maintenance

Preventive maintenance is to keep the equipment operating while considering the costs associated with failure. It is implemented to reduce failure (M. C. Eti, Ogaji and Probert, 2006b). This type of maintenance strategy aims to reduce labour costs and inventory cost (Soh, Radzi and Haron, 2012). Preventive maintenance is carried out after a prescribed time elapses such as when a certain number of units have been produced (Garg and Deshmukh, 2006). According to Phogat and Gupta, (2017), preventive maintenance may refer to calendar time, operating time or the age of an asset. Hence, preventive maintenance is sometimes called planned, historical or calendar-based maintenance (Bengtsson, 2014). Preventive maintenance is important in an organisation as it reduces unexpected breakdowns, thereby reducing costs associated with production and reduction in service or product quality (Soh, Radzi and Haron, 2012). According to Stenström *et al.* (2016), one of the objectives of preventive maintenance is to ensure the reliability, availability, and safety of components.

Preventive maintenance depends on operation and experience. With this type of maintenance strategy, maintenance personnel try to prevent components, subsystems or systems degrading to the point of breakdown. This can only be done through repair, servicing or component exchange at pre-set intervals (Vilarinho, Lopes and Oliveira, 2017). Preventive maintenance is normally done through a probabilistic model of component failure developed from historical data to try to avoid system or component failures (Alaswad and Xiang, 2017).

The maintenance strategy includes simple preventive maintenance and preventive replacement while the system is kept running. Simple preventive maintenance is grouped into categories namely, lubricating, cleaning, adjusting, tightening and simple repairs (Soh, Radzi and Haron, 2012). Preventive maintenance is currently one of the most used maintenance strategies. To sustain an efficiently operating rolling stock and reduce the failure of critical equipment, the concentration has shifted over the years to preventive maintenance.

In the past, reactive maintenance was common; however, due to the need to keep critical components operational and reduce their failure in rolling stock, preventive maintenance began to be implemented by rolling stock organisations. However, its implementation brought about problems such as repetitiveness, errors during maintenance and lack of clear reasons for carrying out some preventive maintenance actions. Rolling stock organisations also have to comply with legislation and rules as stated by safety authorities when it comes to the frequency and procedures of preventive maintenance (M. C. Eti, Ogaji and Probert, 2006b; Rezvanizaniani *et al.*, 2008).

Preventive maintenance helps in reducing reactive maintenance costs and in extending the life of equipment. Production will also increase since unscheduled downtime will decrease, purchasing of spare parts will decrease and this results in up-to-date inventory records (Carretero *et al.*, 2003). According to Soh, Radzi, and Haron (2012), preventive maintenance is also implemented in rolling stock organisations to reduce the probability of failure whilst at the same time improving the overall reliability and availability of the system.

In a railway research study by Lin, Pulido, and Asplund (2015), a preventive maintenance strategy was applied to wheelsets. Preventive maintenance actions were done at set times and points to keep the system running at the desired level. One of the actions undertaken was to re-profile wheelsets after running a certain distance. This research also revealed that the position of the wheelset influences its rate of deterioration.

2.3.2.1 Scheduling

Maintenance is an expensive exercise. It therefore requires an effective maintenance strategy as well as an optimal maintenance schedule to reduce maintenance costs whilst at the same time not compromising on the quality of maintenance (Soh, Radzi, and Haron, 2012). Scheduling can be defined as the bringing of mechanics, tools, materials, unit to be serviced and information needed for job completion to the right place at the right time (Garg and Deshmukh, 2006). Poor maintenance schedules may lead to an organisation incurring high maintenance costs or the schedule might not be executable at all (Peng *et al.*, 2011; Soh, Radzi and Haron, 2012). The inspection of systems, subsystems, and components is done and this is usually the first step in a maintenance schedule. Researchers have tried to address the issue of scheduling through the use of different algorithms such as integer programming, mixed integer programming and genetic programming among others.

The main aim of scheduling preventive maintenance is to meet all the requirements of all rolling stock systems, subsystems and components timeously since tasks which are done too early or too late are associated with unwanted costs (Budai, Huisman and Dekker, 2006). Scheduling results in proper and efficient use of materials, equipment, people and cash flow (Organ *et al.*, 1997). Preventive maintenance scheduling aims to maximise the total priority of the scheduled tasks subject to resource constraints. Most operators tend to do their preventive maintenance during the time that the train service is running. This is done at times when there is less demand for trains from customers and normally timetabling software is used to find the time when trains are not in much demand. An operator in The Netherlands carries out preventive maintenance on trains during the night when there is no or less demand on trains. This helps to eliminate the hazard posed on maintenance personnel from carrying out maintenance tasks while the train is in use. Scheduling this preventive maintenance can easily be done through a cyclic static schedule or at times they make a sacrifice by interrupting the train service and maintaining it during the day by means of a dynamic schedule (Budai, Huisman and Dekker, 2006).

To effectively solve a preventive maintenance scheduling problem, there is a need to make use of several heuristics that can quickly come up with a good schedule. Some scholars have suggested the use of mixed-integer programming, tabu search, genetic algorithm and genetic programming methods (Budai, Huisman and Dekker, 2006; Budai, Dekker and Kaymak, 2009; Gandhare, Akarte and Patil, 2018).

In carrying out preventive maintenance scheduling of rolling stock, one has to integrate routine activities and projects to reduce costs. In coming up with the schedule the planning horizon, number of projects, number of routine maintenance tasks, duration of routine maintenance tasks, frequency of routine maintenance tasks and the period between successive executions of the schedule must be known. The time that has elapsed since the last routine maintenance tasks were conducted, start times of different phases of the project, duration of the project, the maintenance cost for the whole maintenance horizon, as well as the decision variable on the order of carrying out maintenance tasks need to be known (Budai, Huisman and Dekker, 2006; Peng *et al.*, 2011).

To solve the scheduling problem, Budai, Huisman, and Dekker (2006) used a mixed integer programming algorithm. Scheduling preventive maintenance that stretches over a long period normally directs the main focus to be on cost whereas those for a short time focus on train delays and train cancellations. However, to reduce train cancellations, additional maintenance personnel are allocated as well as the use of mathematical models for both scheduling and the assignment of maintenance teams (Peng *et al.*, 2011). Mathematical models also focus on budget constraints and train schedules among many other factors that are affected by a maintenance plan. For a preventive maintenance schedule of short duration, a tabu search is used to quickly derive an optimal schedule. This model can also be expanded to include maintenance costs and team setups. When several maintenance tasks are to be undertaken in a maintenance schedule, resource allocation also becomes part and parcel of maintenance scheduling and this can be done through prioritisation of some maintenance activities over others (Peng *et al.*, 2011).

It is often a common practice to avoid executing maintenance tasks at night, though this would be a perfect time since there will be no or less demand for trains; however, it poses safety risks to maintenance personnel. For this reason, most rolling stock organisations avoid scheduling their maintenance activities at night. Due to the number of factors that need to be taken into consideration, preventive maintenance schedules end up being complex and some organisation end up resorting to the intuition and experience of experts to manually come up with schedules. This leads to more time being spent on scheduling and the results are normally not optimal. The use of Lagrangian relaxations and column generations has proved to be difficult and at times inapplicable in situations where there are several constraints (Peng *et al.*, 2011).

Peng *et al.* (2011) developed a hybrid heuristic approach that finds optimal maintenance schedules and it helped develop a quality solution through feasibility and optimality and shortened scheduling time. The research also emphasised team formulation and specialisation in which a team is given a specific job to perform based on their ability. The schedule should take care of production rates of different teams as this helps in the assignment of duties.

In coming up with a maintenance schedule, some constraints are considered to be soft constraints that can be violated but not without cost. For example, if preventive maintenance tasks are not completed in the given time, maintenance is allowed to continue, rather than releasing trains when the maintenance is not fully complete. This will result in a loss of revenue through the cancellation of some train schedules (Peng *et al.*, 2011).

Maintenance tasks that take a lot of time must be split and be shared among teams. For example, in a preventive maintenance task in which the trains are meant to first be cleaned, oiled and inspected before any other duty such as repairing or replacement is conducted, all teams can be assigned to participate in cleaning, oiling, and inspection of rolling stock (Peng *et al.*, 2011). Figure 2.7 shows a framework that can be used in scheduling maintenance for rolling stock.

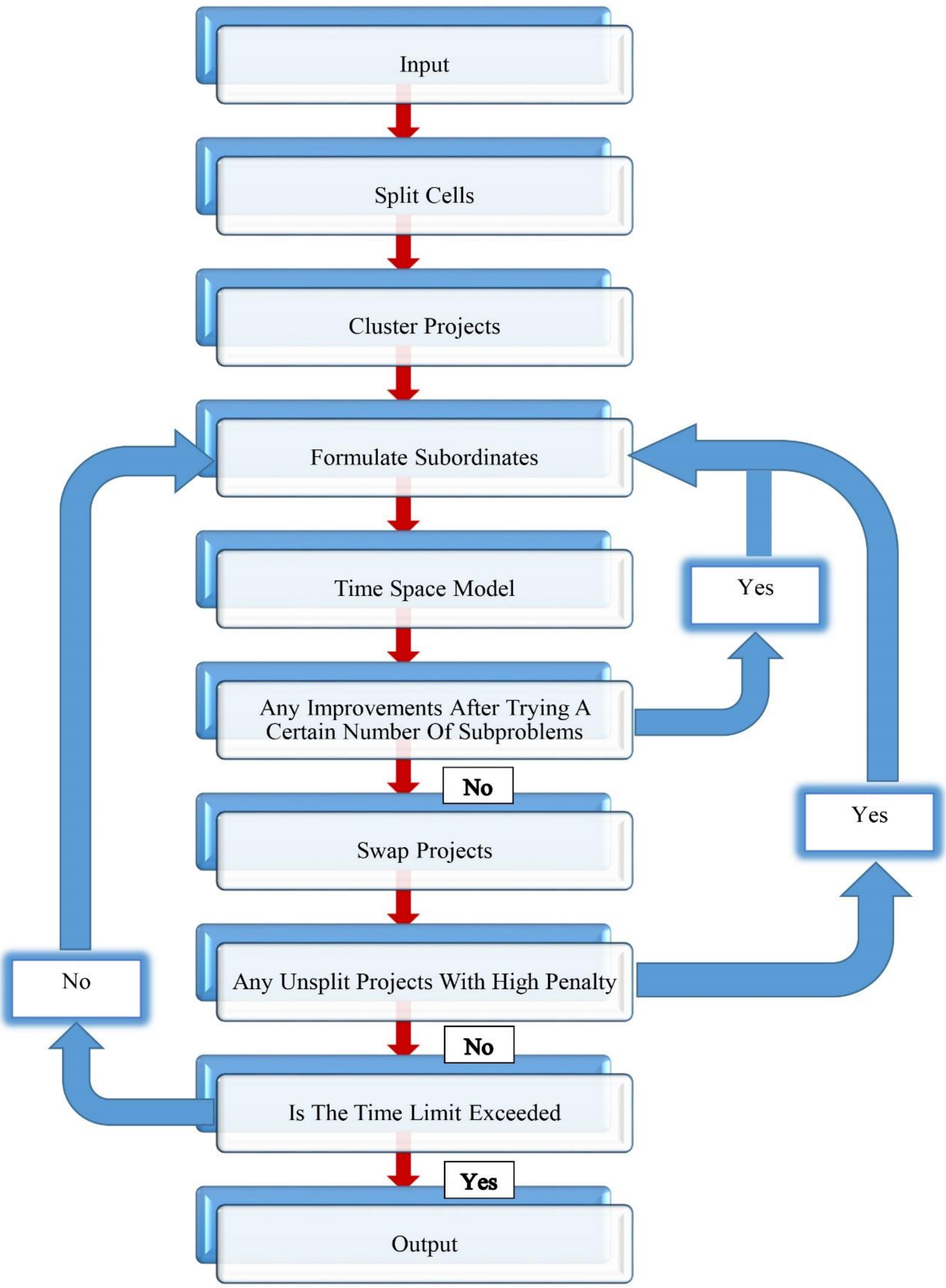

Figure 2.7: Scheduling framework (adopted from Peng *et al* (2011))

In research done by Soh, Radzi, and Haron (2012), preventive maintenance scheduling was done to compute assignments which led to a minimum make span, scheduling all preventive maintenance tasks with optimal time duration and minimising overall costs while at the same time providing the best quality of reliability and availability of the system. In scheduling for preventive maintenance in rolling stock, each maintenance activity needs different levels of manpower, expertise, and duration. All these should be taken into account when scheduling. Soh, Radzi, and Haron (2012) studied the issue of assignments of different groups as well as gang scheduling. This takes care of mutually exclusive tasks which can be done at the same time to reduce spending too much time on maintenance and reducing rolling stock availability. On project splitting, the research proposed the use of a clustering algorithm to come up with an optimal schedule. The four most used scheduling techniques for preventive maintenance on rolling stock are; strategic gang research, heuristic approach, genetic approach and simple greedy heuristics (Soh, Radzi and Haron, 2012).

Some scheduling problems need to be separated in terms of the duration of the maintenance tasks. Tasks that need a longer time to be performed need to be done when trains are least in demand. In these schedules, one needs to stay within the scheduling horizon. Greedy heuristics were used to solve the problem (Budai, Huisman and Dekker, 2006). However, Budai, Dekker, and Kaymak (2009) came up with a better solution as a genetic algorithm, a memetic algorithm and an iterative heuristic using three local search techniques was implemented and a two-phase opportunity-based heuristic was developed.

Sriskandarajah, Jardine and Chan (1998), in coming up with a preventive maintenance schedule for rolling stock for Hong Kong Mass Transit used a genetic algorithm to optimise maintenance scheduling whereas Huggins (2007) used a mathematical model to determine assignments and schedules of maintenance teams to minimise train disruptions.

In a rolling stock organisation, Maróti and Kroon (2007) developed a scheduling model for maintenance up to a month in duration. Andrés, Cadarso, and Marín (2015) analysed rolling stock maintenance that covered days, weeks, months or more, even though the model was tested for the short time duration (maintenance that covers days and months). The proposed model, however, can be used for long-term maintenance duration without much editing of the program.

In the research that was done by Andrés, Cadarso and Marín (2015) it was assumed that trains undergo maintenance after a certain period or after travelling a certain distance and thus they focused on preventive maintenance scheduling looking at various levels of maintenance. These levels can be easily split into two levels, namely low-level maintenance and high-level maintenance.

1. Low-level maintenance

At this level, maintenance takes place after several days or weeks. The trains undergo maintenance checks regardless of whether or not they have developed a problem. The maintenance time window determines how much time or distance a train must operate before they can undergo maintenance. Low-level maintenance is subdivided into daily inspection and monthly inspection (Andrés, Cadarso and Marín, 2015).

According to Andrés, Cadarso, and Marín (2015), a train undergoes daily inspection when it has been operating for the whole day or on two consecutive days. These inspections are normally 1–2 hours in duration for daily inspection and 4-6 hours for monthly inspection. Since these inspections are of short duration, trains are normally available for routing. It is the duty of the maintenance personnel to keep track of these events (when the maintenance was carried out, the faults found, how they were rectified and duration of the process among many other things).

2. High-level maintenance

This level of maintenance takes place after months or years. At this time, trains are unavailable for routing. High-level maintenance is subdivided into large inspection and overhaul inspection. These are scheduled ahead of time including the bay area where the maintenance will be carried out (Andrés, Cadarso and Marín, 2015).

However, the mathematical models that have been highlighted which use different algorithms such as genetic algorithms, integer, linear and non-linear algorithms among others do not guarantee that the schedule will be optimal. This is because these also rely on the input data, so data collected must also be of high quality and be a true reflection of the plant or component (Vilarinho, Lopes and Oliveira, 2017).

2.3.2.1.1 Effect of scheduling on preventive maintenance strategy

From the above discussion, several scheduling factors were highlighted which have an impact on preventive maintenance, thereby influencing rolling stock availability based on the implemented maintenance strategy. These are;

1. The number of teams – Scheduling has to assign maintenance tasks to all teams. This helps in meeting due dates and sticking to the time horizon. Having several teams helps with team specialisation so that the team can have experts in its maintenance tasks. This increases the quality of maintenance strategy being implemented.

2. Team performance – Scheduling should be done on team performance. In allocating duties, teams that take longer to finish should not be given a lot of tasks as this will lead to some maintenance tasks not being done or being done after the stipulated time horizon has elapsed.

3. Time horizon – Preventive maintenance should be carried out within the stipulated time. If more time is spent, it results in an increase in maintenance costs, unavailability of rolling stock and other negative effects, whereas allocation of less time will lead to teams not being able to perform their duties efficiently and effectively. This results in a reduction in the quality of preventive maintenance strategy, unexpected system failure and an increase in rolling stock unavailability.

4. Team assignments – This should be done based on expertise. Teams should be assigned tasks that they have the know-how to perform. This improves the efficient execution of maintenance tasks thereby increasing the quality of the implemented maintenance strategy.

5. Time intervals on when to repeat tasks – Mathematical models based on input (such as equipment age, rate of failure and technical condition) should be able to state when relevant preventive maintenance tasks should be carried out. Otherwise, the equipment might fail before the next maintenance. In cases where preventive maintenance is calendar-based, preventive maintenance strategy might compromise the availability of rolling stock as it might fail before preventive maintenance is carried out as per the schedule. It may also result in the increase of maintenance cost in cases where the strategy is carried out when there is no need and train trips are cancelled solely based on the calendar, not on the need for preventive maintenance.

6. Allocation of resources based on priority – The scheduler should be able to allocate resources based on priority. In cases where this is not done, poor maintenance procedures might follow.

7. Optimal schedule – A proper schedule is one that can be implemented. If a poor schedule is proposed, the maintenance strategy might fail to meet its objectives as the schedule will be impossible to implement.

8. Abstract models – Models that present a huge gap between theory and practice result in poor maintenance schedules as they fail to incorporate all industry dynamics. Maintenance personnel at times fail to use and understand these models.

According to Eti, Ogaji, and Probert (2006), proper planning and scheduling improve the effectiveness of a maintenance strategy, which helps to avoid over-maintenance. Over-maintenance leads to the wastage of resources and an increase in downtime while maintenance is being done whereas under-maintenance leads to unexpected breakdowns.

2.3.2.2 **Implementation**

In implementing preventive maintenance, the focus must be on resources available through establishing those that are needed, the level of skill of personnel, management commitment and the influence of other departments. According to de Jonge, Teunter and Tinga, (2017), it is easy to implement preventive maintenance as only service time needs to be recorded.

1) Resource availability

Development of maintenance strategies must take note that resources are not always enough thereby affecting the quality of maintenance strategy being implemented (Bertolini and Bevilacqua, 2006). Several resources come into play when it comes to maintenance procedures. These include;

a) Costs associated with maintenance activities.
b) Maintenance personnel – there should be enough maintenance personnel. Workers should not be overburdened with work.
c) Spare parts- these are needed for replacement of parts that have exceeded their useful life.
d) Time.
e) Tools needed.

A clear plan that shows the relationship between preventive maintenance and resources must be established. This helps in identifying resources that are needed as well as when they are needed (Organ *et al.*, 1997).

According to Vilarinho, Lopes, and Oliveira (2017), frequent preventive maintenance actions can lead to depletion of resources and at times the maintenance tasks will be unnecessary. Therefore, the number of times maintenance tasks are carried out and how they are implemented has an impact on the preventive maintenance resources.

The resources spent on each activity must be recorded. These help in analysing and assessing the maintenance strategy being implemented and in preparation for future maintenance plans as the records give an informed estimate on the type and quantity of resources needed to perform a certain maintenance task (Stenström *et al.*, 2016).

2) Level of skill of personnel

The most effective method of implementing a maintenance strategy is to ensure that all personnel involved are properly trained in the activities they will perform and all should be determined to solve the problem at hand. Most of the time maintenance is carried out by unskilled personnel leading to compromise in the quality of maintenance procedures and equipment availability (M. C. Eti, Ogaji and Probert, 2006b). Maintenance personnel should:

a. have the necessary technical skills to perform maintenance tasks and understand the equipment they are working on.

b. be able to share information with the rest of the organisation on issues that need a collective effort.

c. be able to work in teams.

d. be able to track and record maintenance activities (M. C. Eti, Ogaji and Probert, 2006b).

e. analyse data such as the one from the Computer Maintenance Management System (CMMS). Proper data analysis will help to figure out if there is a trend in failure modes and failure rates hence helping to plan accordingly (Vilarinho, Lopes and Oliveira, 2017).

In another research report, Waeyenbergh and Pintelon (2002) stated that for maintenance strategies to be effective it is important for maintenance personnel to:

a. be highly skilled.

b. receive continuous training for continuous improvement on maintenance issues.

c. be able to use computer support for stock tracking, personnel management, job order tracking, historical data processing, and efficient document control.

d. be familiar with maintenance techniques and methodologies.

Organ *et al.* (1997) advocated for maintenance personnel to always seek advice from experts. This helps in the continuous improvement of individuals and teams and it eliminates reoccurrence of maintenance problems such as unexpected breakdowns. According to Stenström *et al.*, (2016), inputting data on CMMS, data collection and data analysis should be done by a competent person who has been properly trained.

3) Management Commitment

For preventive maintenance strategy or any other to be effective, management must be committed to the plan. Being in management consists of more than controlling activities being performed by individuals. It requires management commitment to the vision and mission of the maintenance department. This can be done through making funds available to enable the efficient performance of the maintenance department (Eti, Ogaji and Probert, 2006b). Lack of provision of funds leads to the unavailability of spare parts and a drop in maintenance personnel motivation. In such a case, the quality of maintenance drops (Cromie *et al.*, 2015).

Leaders should therefore formulate goals with workers in mind and promote individual enhancement. They need to focus on how to motivate maintenance personnel to perform the tasks. For workers to perform duties effectively, they have to be motivated through financial and non-financial means. Management should also create an environment for teamwork, where departments are divided into teams (Eti, Ogaji and Probert, 2006b). According to Dhillon (2010), working in teams helps to reduce human errors in maintenance.

Management should also consider worker safety during maintenance. Where workers feel unsafe, they do not perform their duties efficiently as they will be worried about their safety. Continuous learning, personal improvement, and teamwork should be encouraged to improve the performance of workers (Eti, Ogaji and Probert, 2006b).

Management should also be able to plan and control a preventive maintenance strategy (Waeyenbergh and Pintelon, 2002). Planning to have an effective plant is easy; however, having workers to be effective in their duties is often difficult. Management has, therefore, to invest in training in skills and enhancement of maintenance personnel. This brings about positive results regarding the implementation of preventive maintenance and any other maintenance strategy being implemented. In preventive and predictive maintenance strategies, enhancement of personnel promotes trust and openness, problem-solving skills and a change of attitude (Organ *et al.*, 1997).

4) Influence of other departments

According to Waeyenbergh and Pintelon (2002), the influence of other departments in the execution of maintenance procedures and strategies can no longer be ignored. Departments within an organisation coexist. The success of the organisation depends heavily on how departments are integrated. Hence, the success of a department is also dependent on that of other departments.

To achieve success, organisations need to implement effective interdepartmental communication and this will lead to the internal coherence of departments. Poor communication among departments can lead to an increase in stress levels among employees, resulting in poor performance. Communication between departments is key as workers are different individuals with different experiences who are bound to make different decisions at different times. Communication helps in keeping all departments on the same page in terms of goals, needs and work progress of each department (Gondal, Shahbaz, and Shahbaz, 2012).

Communication is important in motivating workers to perform their duties and activities effectively and efficiently. Disagreements between departments result in poor communication and the quality of products and services drops significantly (Gondal, Shahbaz, and Shahbaz, 2012).

2.3.2.3 Data collection

Organisational knowledge and the full participation of everyone in maintenance issues is vital. In implementing a maintenance strategy such as preventive maintenance, full details of operation and equipment condition and historical data are needed. These also help in formulating the most effective maintenance strategy that can be applied to a system, subsystem or component.

Detailed information about the system, subsystems and components must be taken into consideration because failure to do that leads to maintenance strategies not reaching their full potential of ensuring the continuous running of the system and avoidance of unexpected failures. Therefore, there is a need for data collection on the organisation’s operating environment, type of equipment being used, its condition, how it has been maintained in the past and its historical failure data (Waeyenbergh and Pintelon, 2002).

It is extremely hard to collect, analyse and structure data when there is no computer database. In cases where data is not gathered properly, it leads to distortion of information and at times important information may not be available. This leads to poor maintenance procedures being implemented (Waeyenbergh and Pintelon, 2002). In cases of preventive maintenance, it leads to the incorrect timing of scheduling and also poor preventive maintenance procedures such as implementing replacement instead of repairing.

Data gathering is a tedious exercise that needs much time and work and failure to conduct this exercise properly leads to some maintenance strategies being hard to implement. Proper data gathering is an important step in implementing a relevant maintenance strategy as well as for continuous improvement (Waeyenbergh and Pintelon, 2002). Two of the most common methods of collecting data on maintenance issues, according to Waeyenbergh and Pintelon (2002) are through explicit knowledge and tacit knowledge. These concepts are explained next:

1. Explicit knowledge

This is the knowledge that one gets from the company’s records. This can be obtained from filed written records or a computer database. It may consist of;

a. Type of failure of each component;

b. Components that are much prone to failure;

c. Consequences of each failure;

d. The failure rate of components;

e. Time spent on repairing/replacing;

f. Personnel involved in the maintenance activities;

g. Period of operation of components.

These help in establishing the most efficient maintenance strategy to be implemented. For example, in cases of preventive maintenance, it helps to decide which task to implement such as repairing or replacement. In cases where the component has exceeded its useful life then the replacement task will be preferable. In such cases, repairing leads to a compromise in the quality of preventive maintenance as a strategy as the component may fail unexpectedly even soon after repair, as it will already have exceeded its useful life.

2. Tacit knowledge

This is knowledge which emanates from within the workers themselves. It is derived through work experience, skills, abilities, and feelings. It is often one of the forgotten types of knowledge within the organisation. Tacit knowledge tends to be an important way of gathering data about the components and maintenance issues where there are no written records. It can lead to more or less the same information that one gets from written records. However, this method is very subjective and it can therefore lead to incorrect information and lack of details.

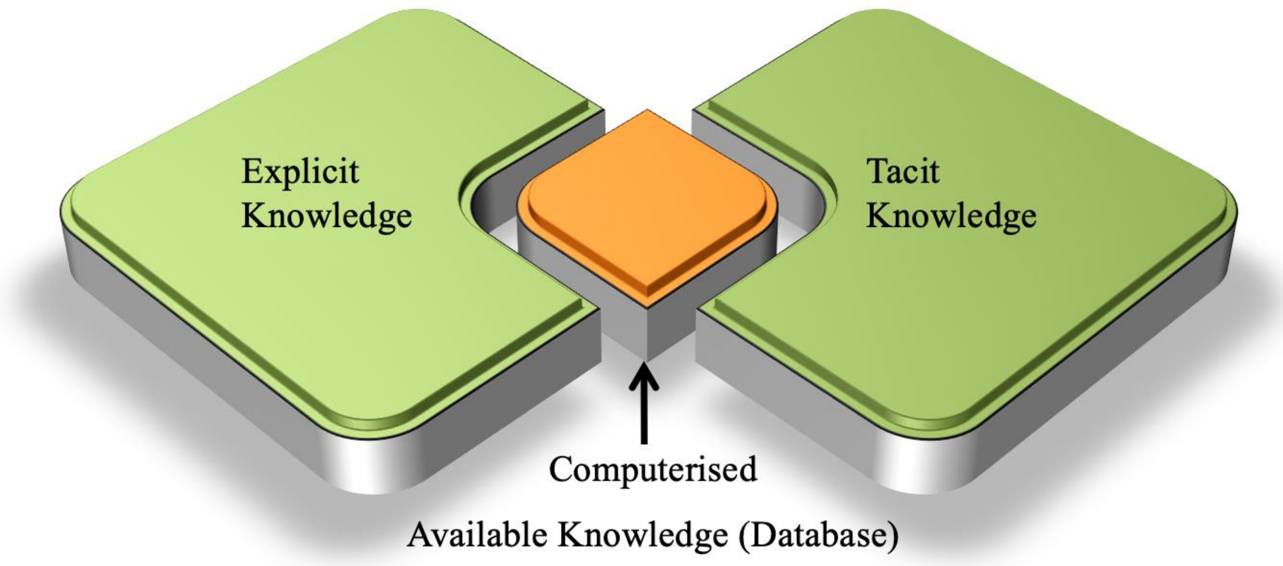

Figure 2.8: Gathering knowledge and CI (adapted from Pintelon et. al (2002))

In cases where information is stored in computer systems such as the Computer Maintenance Management System (CMMS), all the required information must be available and data must be properly standardised. Failure to do so leads to the incorrect analysis of component failures and hence it has an impact on the component availability analysis. Therefore, in capturing information such as failure mode, failure effects, component age, and all other information must be properly stated and completed in full (Vilarinho, Lopes and Oliveira, 2017).

Figure 2.9 shows a proposed way of inputting data into the CMMS. All failure events must be recorded with the failure mode. When a plant or system or subsystem has more than one component of the same type and model, CMMS should be able to distinguish between the two (Vilarinho, Lopes and Oliveira, 2017).

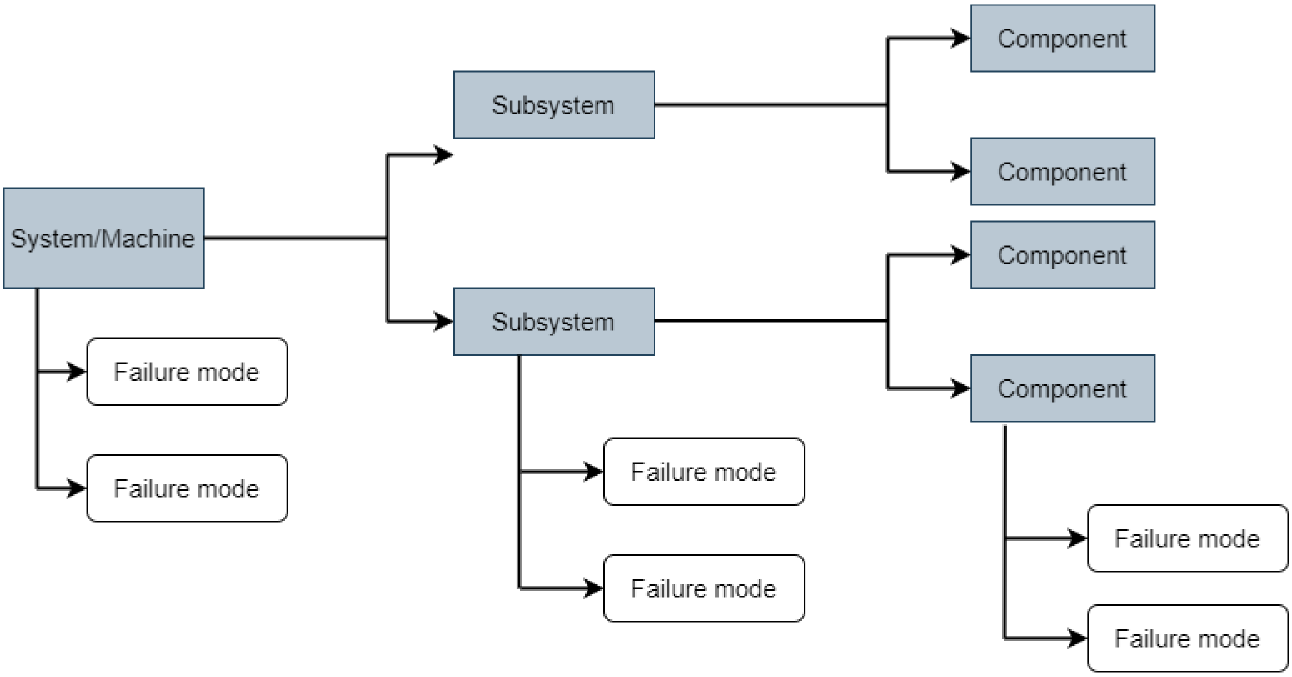

Figure 2.9: Failure tree structure of machines (adopted from Vilarinho et. al. (2017))

2.3.2.3.1 Influence of data gathering on preventive maintenance

Data gathering has the following influence on preventive maintenance:

a. Lack of written records leads to no information being available on the historical data of components, resulting in poor scheduling and unexpected component failures.

b. Wrong information or lack of it results in the implementation of the wrong maintenance tasks, for example, repairing a component that has exceeded its useful life.

c. Availability of written records leads to proper scheduling for maintenance thereby avoiding unexpected failures of components.

d. Availability of correct and detailed historical data of components helps in securing necessary resources as and when they are needed. These may include spare parts, tools and skilled personnel.

e. Failure to analyse data properly can lead to misinformation. One should have a complete understanding of the underlying problem when analysing data (Vilarinho, Lopes and Oliveira, 2017).

2.3.2.4 Summary of preventive maintenance

Though preventive maintenance involves a lot of work in terms of scheduling, implementation and gathering data, it does offer some merits that seemed impossible with run-to-failure maintenance. These, as summarised by Horner, R.M.W.; EL-Haram, M A; Munns, (1997) are:

1. Reduces the probability of failure.
2. Avoids sudden failures.
3. Maintenance can be scheduled and carried out when it is convenient.
4. Maintenance costs can be reduced by eliminating costs associated with breakdown.
5. Downtime is reduced, thereby increasing system availability.
6. It improves the health and safety of maintenance personnel.

However, it also has its demerits and these can be summarised as follows:

1. It is carried out regardless of the condition of the equipment and this results in unnecessary tasks being undertaken on components that would have remained safe and reliable for a longer time.
2. Carrying out maintenance tasks may undermine the condition of the system/subsystem/ component due to human error during the execution of maintenance task.
3. As the maintenance strategy is scheduled, it may result in tedious work in terms of spare part procurement and ensuring the availability of labour during the predetermined time (Horner, R.M.W.; EL-Haram, M A; Munns, 1997).

Figure 2.10 shows a framework that was proposed for organisations trying to implement a preventive maintenance strategy. The framework covers some of the aspects that have been highlighted in this section such as data collection and scheduling.

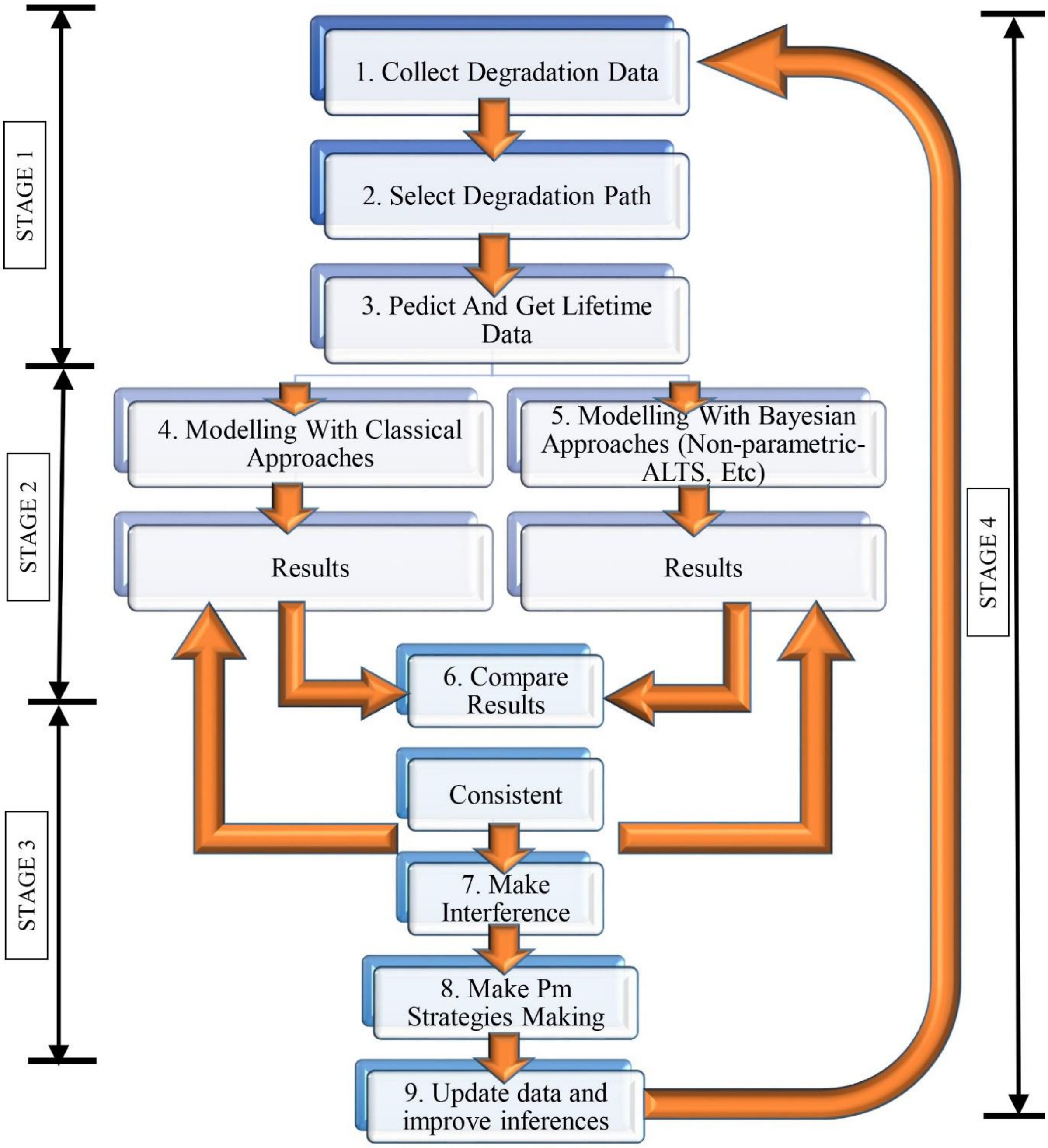

Figure 2.10: PM implementation framework (adapted from Lin et. al.Pulido (2015))

As put by Ben Said *et al.*, (2016), the drawbacks of preventive maintenance are over- and under-engineering that lead to increased costs and/or reduced production capacities.

2.3.3 Predictive maintenance

Predictive maintenance was initiated to reduce failure rates, repair rates, assess equipment conditions in real time, detect problems of equipment before they breakdown, reduce downtime and increase the readiness of the maintenance department and the organisation (Mitchell *et al.*, 1995). This type of maintenance strategy involves estimating the time of equipment failure by detecting early signs of deterioration that make maintenance proactive. It helps to improve reliability, availability, safety, efficiency, product/service quality and protect the environment (Selcuk, 2017). According to Phogat and Gupta, (2017), a lot of monitoring methods are in place nowadays, including ultrasonic testing, lubrication analysis and vibration monitoring. According to Alaswad and Xiang (2017), the objective of predictive maintenance is to reduce unnecessary maintenance tasks and other problems that come with preventive maintenance.

According to research done by Lin, Pulido, and Asplund (2015) in the railway industry, where the organisations are worried about the reliability of rolling stock and where the focus is on wheelsets, both preventive and predictive maintenance strategies are used. A predictive maintenance strategy is implemented to predict wear, fatigue and failures and preventive maintenance is used for re-profiling and lubrication. According to Li *et al.* (2017), predictive maintenance helps the railway industry to achieve high safety, reliability, and availability.

With this type of maintenance, those in the maintenance team carry out maintenance tasks at intervals based on equipment condition. Assessing the condition of the equipment is normally done by analysing it for vibrations, oil quality, temperature, voltages and currents among other possibilities (Bengtsson, 2014). According to Selcuk (2017), predictive maintenance is heavily linked to sensor technology, communication and computer technologies such as the Internet of Things and radio-frequency identifications. This helps the maintenance strategy to be more efficient, applicable, affordable and common in diverse industries and in unsafe environments where it is hard for a human being to do inspections such as in areas of high temperatures and pressure.

Several software tools for predicting the wear of wheelsets in the railway sector have been proposed. From these software tools, data has been extracted and analysed to improve the lifetime of wheelsets and thereby increase both reliability and availability of rolling stock (Skarlatos, Karakasis and Trochidis, 2004; Stratman, Liu and Mahadevan, 2007; Pombo *et al.*, 2010).

Predictive maintenance is now gaining more acceptance. This is as a result of the increase in knowledge, technical skills, the ability to monitor, store and analyse the condition of equipment, the existence of different types of sensors and the vast application of Wireless Network Systems (WNS) (de Jonge, Teunter and Tinga, 2017; Selcuk, 2017). According to Selcuk (2017), these systems also help in evaluating available data, determining the right actions to be undertaken in maintenance strategies such as mobilising maintenance personnel, tools and parts and determining the right time for maintenance activities to be undertaken.

The application of predictive maintenance is dependent on the organisation. Some organisations use highly sophisticated methods utilising technology to detect or assess the condition of their equipment whereas others use less advanced technological methods, such as visual inspection (Bengtsson, 2014). Predictive maintenance helps detect signs of faults and then prompts for maintenance actions to be undertaken at the right time thus it provides information that is both diagnostic and prognostic as it gives details on what is wrong, where it is wrong and what is happening among other information (Selcuk, 2017).

Predictive maintenance is based on two assumptions, namely that the rate of deterioration is low enough to enable its detection before failure, giving ample time to carry out maintenance activities and that the system cannot be left to fail as this has huge consequences on costs, safety and the environment (Selcuk, 2017).

Many researchers have come up with ways of implementing predictive maintenance, starting with how to assess the condition of the equipment. Organisations that are almost fully automated use an online condition monitoring system. These give real-time assessments and can send visuals of the equipment's condition. According to Bengtsson (2014), there are certain demands of the online condition monitoring system, namely:

1. Real-time application;
2. High reliability;
3. At the early stage, alert when the fault is impending, so that maintenance can be planned when an asset is not being used;
4. Identification of the fault and where the fault is located;
5. Classify faults in different categories, when a fatal fault occurs automatic shutdown should be a possibility;
6. The alerts should be easy to understand;
7. The system should be connected to a superior computer.

Predictive maintenance allows for a much more effective planned maintenance action than those of preventive maintenance. The performance of the predictive maintenance strategy depends on the rate of the deterioration process, the severity of failures, installation time, the accuracy of condition measurements recorded and the point perceived to be the point of failure of the equipment. It should also be noted that predictive maintenance should be implemented when its benefits are more than the costs of implementing it (de Jonge, Teunter and Tinga, 2017).

2.3.3.1 Scheduling

In predictive maintenance, scheduling of carrying out failure preventive actions is done when the equipment’s condition deteriorates. According to de Jonge, Teunter and Tinga (2017) and Horner, R.M.W.; EL-Haram, M A; Munns (1997), predictive maintenance provides better scheduling as it is based on the condition of the equipment and this is the reason for applying maintenance tasks. The timing of maintenance tasks is determined by the observed condition of the components. Therefore, maintenance scheduling is done when the equipment condition deteriorates to a certain predetermined level. If that level is exceeded without maintenance being applied, then failure will be imminent.

Scheduling in predictive maintenance helps to prevent over-maintenance, under-maintenance and unnecessary part replacement (Selcuk, 2017).

2.3.3.2 Implementation

Implementation of predictive maintenance is sometimes difficult. This is due to the need for the use of specialised components, especially in online monitoring. The biggest challenge, therefore, becomes effective management, utilisation, and communication within the organisation. The predictive maintenance system should be built with human, technical, and organisational aspects in mind as these form the core factors in implementing the predictive maintenance strategy. Implementation of predictive maintenance requires maximum integration of sensors, feature extraction, classification and predictive algorithms (Bengtsson, 2014).

As the need for effective implementation of predictive maintenance is growing, maintenance personnel need to properly and correctly carry out predictive maintenance duties (de Jonge, Teunter and Tinga, 2017). Several frameworks have been proposed to implement a predictive maintenance strategy. Mitchell *et al.* (1995) proposed an eight-step method for implementing this strategy. The method consists of developing a clear proper maintenance plan, assignment of responsibilities, determining the equipment needed, purchasing of needed resources, training of employees and implementing the programme.

According to Selcuk (2017), a predictive maintenance strategy implementation plan should consist of data acquisition, data processing, and maintenance decision-making.

1) Resource Availability

Any organisation that seeks to implement predictive maintenance has to commit to purchasing condition-monitoring equipment and its installation. These include sensors and Wireless Network Systems (WNS), computer management systems, equipment hardware and software (Selcuk, 2017).

Failure to purchase condition-monitoring equipment leads the organisation to rely heavily on the senses of its workers for this purpose, such as them using their eyes for visual inspection. However, the procedure becomes subjective as analysis depends on the one carrying out the inspection, based on their level of personnel expertise and other factors.

2) Level of skill

Maintenance personnel cannot be ignored as their skills and expertise are of paramount importance. In predictive maintenance humans are needed to:

a. Collect information sometimes through their senses such as hearing for vibration inspection;

b. Correctly analyse the system, subsystem, and components;

c. Diagnosis based on collected information;

d. Correctly determine the maintenance actions to be taken;

e. Determine when maintenance should be undertaken;

f. Determine the components that need maintenance;

g. Determine the resources needed to carry out the identified maintenance activities.

According to Mitchell *et al.* (1995), there is a need for proper training of maintenance personnel. Workers should be trained in the collection and interpretation of condition-monitoring information based on visual inspection, vibration, online visuals and predictive maintenance techniques.

Although much progress has been done on monitoring systems, however, maintenance personnel remain a key aspect of this maintenance strategy. Most organisations continue to rely greatly on the senses of its workers such as sight, hearing and touch. These are used in visual inspection and are used to gather much data in determining the condition of the equipment. For most organisation implementation of predictive maintenance remains complex and costly due to components for condition monitoring that need to be purchased as well as training of maintenance personnel on this new technology. Some organisations have resorted to outsourcing the services of experts (Selcuk, 2017).

3) Inspections

Predictive maintenance relies heavily on the information from inspections as well as sensors in cases where an online condition-monitoring system is not being used. In such situations, the inspections should be of high quality to influence sound decision-making and implementation. The rate of inspections, therefore, becomes a factor such as how many times inspection is done per period or how often is the system being inspected (Stenström *et al.*, 2016).

Over the years, predictive maintenance has assumed perfect inspections. However, in practice, it is not normally the case. Inspections can be divided into three categories namely perfect, partial and imperfect. Perfect inspections are the ones that give a true reflection of the component's condition whereas imperfect inspections do not give a true reflection of the component's condition due to human errors, the tools being used or for other reasons (Alaswad and Xiang, 2017). It is, therefore, important to assume imperfect conditions in practice. This would be where some defects were not detected or detecting a fault which is not there. It should also be noted that it is difficult to maintain a constant level of inspection quality as this depends on several factors such as the inspector, time of inspection and the tools being used.

The quality of inspections also depends on the number of inspecting personnel, their level of skills, availability of inspection tools and the time given to carry out inspections (Stenström *et al.*, 2016).

Alaswad and Xiang (2017) propose three main inspection schedules under predictive maintenance and these are;

a. Continuous monitoring – Normally an alarm is set which notifies machine users as soon as a defect is detected. This tends to be an advantage as it eliminates unnecessary inspections of the systems and maintenance activities. Condition monitoring is normally used in nuclear power plants and aerospace components. However, it has its disadvantages, as spelt out by Jardine, Lin, and Banjevic(2006), such as being an expensive method of inspection as well as a large amount of noise from the large flow of data. The method is also inapplicable in some environments such as the monitoring of pipes that are underground.

b. Periodic – It influences the effectiveness of a maintenance strategy. It also affects maintenance costs and system availability. However, in some cases where inspection is costly, it is frequently difficult to carry out periodic inspections. Repairs are done if the system is above the set threshold condition for repair but still below that of replacement. If it is now below the threshold for repair, replacement is done. Otherwise if the system is still above both the thresholds for replacement and repair, it is left unchanged and the next inspection time is determined by its condition after the inspection.

c. Non-periodic – This type of inspection is normally carried out at the first stages of the system when it is still new and the number of inspections increases as it ages. Due to the low numbers of initial inspections, this results in some cost savings on inspections. The demerits of non-periodic inspection are that it leads to a lot of documentation and scheduling or sometimes rescheduling. In non-periodic inspections, as the number of reschedules increases so do human errors.

According to Do *et al.* (2015), it is important for an organisation to determine the Remaining Useful Life (RUL) of components through Prognostics and Health Management so that helps in planning for the next inspection. In situations where continuous monitoring is not being implemented, establishing RUL helps in scheduling inspection and hence maintenance before system failure.

Table 2.1: Merits and demerits of PdM inspections (adaption Alaswad and Xiang (2017))

Inspection Frequency	Advantages	Disadvantages
Continuous monitoring	• Gives real-time data on the condition of the system	• High inspection costs • Unnecessary maintenance actions caused by inaccurate diagnostics
Periodic inspection	• Cost-effective	• May result in higher failure costs • More documentation work • Difficult to implement
Non-periodic inspection	• Most cost-effective	• May result in higher failure costs • More documentation • Difficult to implement

On continuous monitoring, the position of sensors influences the quality of inspections. Research done by Li *et al.* (2017) on on-board health monitoring systems for railway vehicles shows that sensors can only be installed at selected positions on the rail thus providing monitoring only at those points. Sensors which can provide real-time inspections and give a signal once a defect is detected include accelerometers, gyros, noise sensors such as microphones and global positioning system (GPS). All these are used to identify track irregularities, location, and speed of trains among other things. An example of a health monitoring system particularly in railway vehicles is the Kalman fitter. Smart algorithms have also been developed to analyse data from sensors. Figure 2.11 shows an example of a rail corrugation detection system.

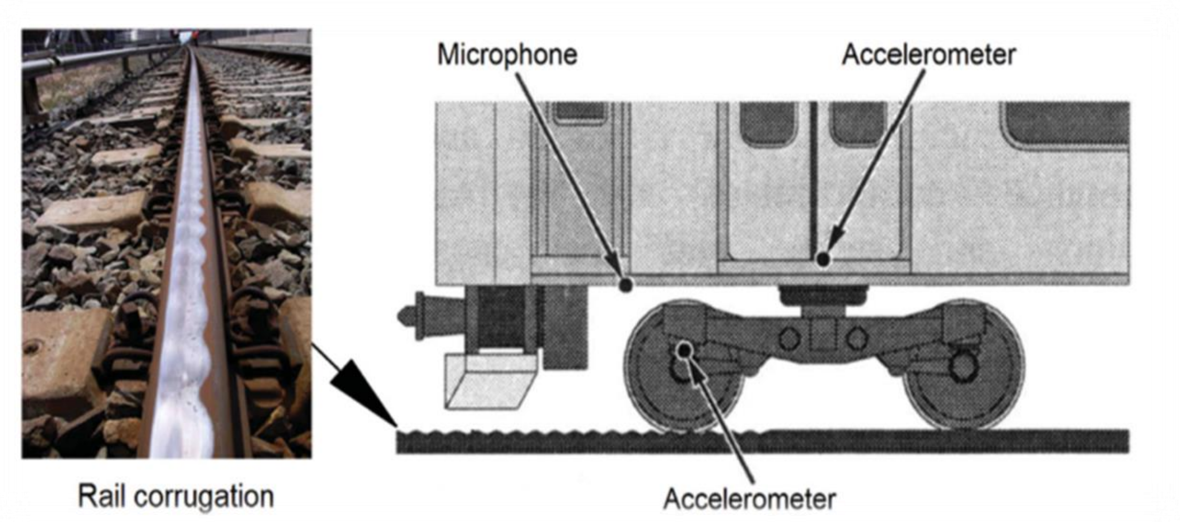

Figure 2.11: A rail corrugation detection system used in Japan (adapted from Li et al. (2017))

On-board train monitoring systems should focus mostly on wheel-rail health monitoring, suspension health monitoring, vehicle component health monitoring and running state monitoring. The wheel-rail monitoring system gives the impact between the wheel and the railway line, detects low adhesion, track irregularities, the flatness of the wheel, rail corrugation and early signs of derailment. Suspension monitoring gives real-time monitoring of the suspension parameter degradation and the vehicle component focuses on detecting defects on vehicle components such as axles, bearings, cold and hot wheel detection and axle crack detection (Roger, 2011; Li *et al.*, 2017).

However, some difficulties come with implementing these health monitoring systems. Running state monitoring is the simplest where only the on-board GPS element is used to identify the real-time location and the speed of the railway vehicle. On vehicle component monitoring, thermal sensors, microphones, and ultrasonic sensors are needed (Weston *et al.*, 2015).

The monitoring system consists of two main stages: the data acquisition stage and data analysis. Data acquisition is the one that has been largely described in the previous paragraphs. Data analysis depends on the level of predictive maintenance implementation in an organisation. In some organisations, they still rely on their maintenance personnel to analyse data from these sensors which therefore brings up the issue of proper training of personnel to ensure accurate analysis.

In a more advanced predictive maintenance environment, smart algorithms are used for data analysis. These tend to render a better quality of analysis than human beings provided they are not faulty. Figure 2.12 shows how some railway organisations implement their data analysis through these technological advancements.

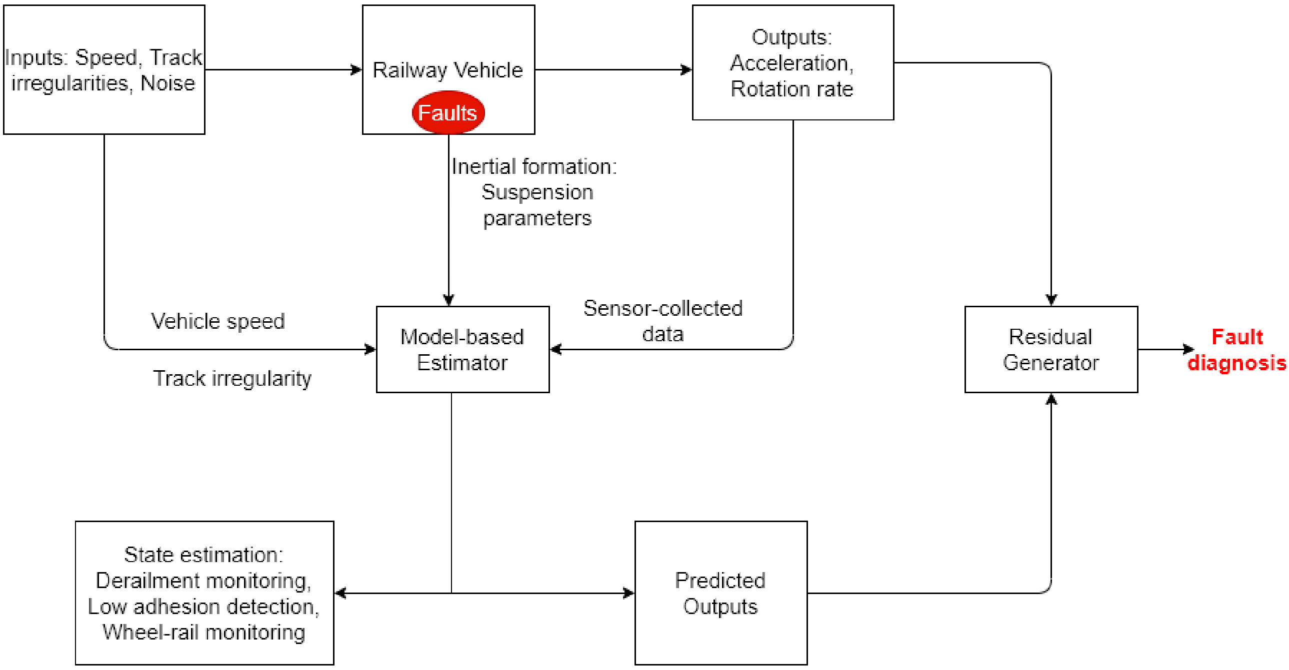

Figure 2.12: Model for monitoring systems for railway vehicles (adapted from Li et al. (2017))

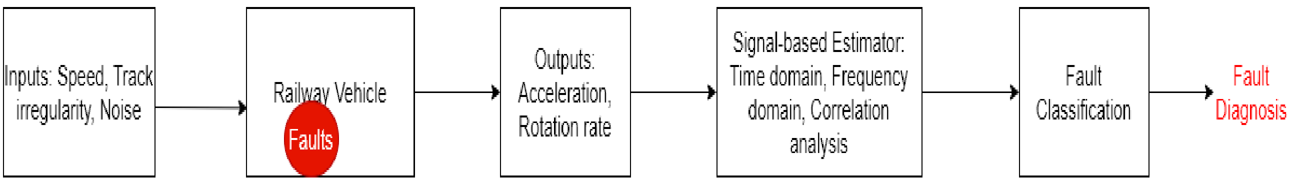

Figure 2.13: Signal-based monitoring systems for railway vehicles (adapted from Li et al. (2017))

As shown in Figure 2.13, signal-based processing methods which are used in railway vehicles to analyse monitoring outputs can be divided into different categories, namely time-domain methods, frequency-domain methods, time-frequency methods, and correlation-based methods.

Time-domain methods collect vibration signals which include maximum value, minimum value, mean value, RMS value, peak factor, shape factor and impulse factor. These have the disadvantage of their analysis results being easily affected by environmental noise, shock, and vibrations whereas frequency-domain methods are used to acquire more intuitive fault relevant features (Li *et al.*, 2017).

2.3.3.2.1 Influence of implementation on predictive maintenance strategy

The following factors based on implementation, affect the quality of predictive maintenance either negatively or positively depending on how they are handled. According to de Jonge, Teunter and Tinga (2017), these factors are:

1. Planning time;
2. Level of condition monitoring;
3. A variation on the failure mode;
4. Availability of condition-monitoring equipment;
5. The ability of maintenance to store and analyse data from conditioning-monitoring equipment;
6. Risks associated with lack of experience in strategy implementation;
7. Requires dynamic scheduling, so the organisation should be capable of changing schedules as to when the need arises;
8. Receiving a signal that equipment has deteriorated depends on the prediction accuracy of the condition-monitoring equipment;
9. The time that elapses between receiving the signal that equipment is deteriorating and the time the equipment fails depends on the prediction precision of the condition-monitoring system;
10. Prediction depends on inspections conducted and signals provided;
11. Repairman not continuously available;
12. Availability of spare parts;
13. The time that elapses between receiving a deterioration signal and the time maintenance activities are carried out.

Selcuk (2017) provides more factors that affect the implementation and success of a predictive maintenance strategy. These are;

1. Determining the components that need to be monitored;
2. The parameter used to indicate the level of deterioration;
3. Techniques used in implementing the maintenance strategy (techniques with a certain level of sensitivity to the condition of the machine, how they are affected by changes in the operating environment, etc.);
4. Finding where to install sensors;
5. Coming up with a threshold for different variables;
6. Determining inspection intervals;
7. Choice of methods to be used to manage the predictive maintenance strategy programme such as computer maintenance management systems.

2.3.3.3 Data collection

In preventive maintenance, the data collected is normally the assessment of the condition of the system, subsystems or components. Therefore, data collection for this type of maintenance strategy depends on the personnel (in both gathering and analysing data), condition-monitoring systems and the level of precision and accuracy of the condition-monitoring system (Selcuk, 2017).

Data should be gathered when the system is still in good condition so that it forms a point of reference. Collected data should be turned into information. Actions are undertaken based on this information.

2.3.3.3.1 Influence of data collection on predictive maintenance strategy

Data gathering has the following influence on the quality of predictive maintenance:

1. It sometimes needs expensive equipment to monitor;
2. Maintenance personnel must be trained to gather data;
3. Personnel must be trained and be able to interpret the gathered data correctly.

2.4 Optimisation of Maintenance Strategies

The optimisation of maintenance strategies helps to increase the effectiveness of different maintenance strategies. According to Ben Said *et al.*, (2016), the optimisation of maintenance strategies ensures an increase on the inspection effectiveness, repair effectiveness and reduction in maintenance-induced failures.

Maintenance optimisation can be done by using a mathematical model in which the benefits of maintenance and the cost of carrying out maintenance activities are quantified and balanced. Moreover, it aims to compare maintenance practices, determine the number of inspections and determine effective maintenance schedules and plans (Vilarinho, Lopes and Oliveira, 2017).

According to Cane (2011), apart from having several factors influencing the safety, reliability, and availability of plant assets, maintenance takes the central stage. The emphasis is therefore directed to the management and implementation of effective maintenance strategies to improve the effectiveness of maintenance strategies one has to go through;

1. Benchmarking

This is done through checking the age of the plant, its operational ability and the effect of maintenance once carried out on it. When all has been done, it leads to the development of programmes to increase and improve personnel skills as well as procedural deficiencies.

At this stage, the organisation can use historical data to check the past performance of the plant, the number of maintenance strategies that have been carried out so far as well as the impact of these strategies at that time. Upon getting this data it can be used for comparison with the current condition of the plant.

Finally, the organisation can use the obtained data to benchmark itself with the best practices being implemented by other organisations. The plants are benchmarked in terms of performance and effectiveness of maintenance practices. Moreover, management practices can be benchmarked as well since management plays a pivotal role in the performance of a plant. To establish the risk of safety and availability of equipment in an organisation, one has to take into account the historical performance of the system, asset management processes and programmes and effectiveness of the implementation of the programmes (Cane, 2011; Van de Pieterman *et al.*, 2011).

In assessing the historical performance of the system, analysis is done from component level up to system level. Through that, maintenance personnel can determine existing and potential safety, availability and reliability of critical components and also establish future performance requirements (Cane, 2011; Van de Pieterman *et al.*, 2011).

For a management programme audit, all information concerning the system must be gathered. The information may include the design of the system, how it is operated, the impact of the operation on its condition and how it is maintained. Competent people who understand equipment design, operation, and maintenance must carry out these tasks (Cane, 2011).

In assessing the implementation programme, data gathered as well as recommendations given by the person who did the inspection must be taken into account. Most of the time such information is not prioritised. The information may include some tasks that are not being performed to maintain the system at an optimal level (Cane, 2011).

2. Assessing the condition of the plant in terms of safety, reliability, and availability

This process can be carried out through the implementation of Risk-based Inspection and maintenance of the whole plant from components to subsystems up to the whole system. Technical methods can then be applied for assessing the conditions of the plant.

In most cases, condition assessment and benchmarking are closely linked to management practices to the extent that optimising management practices ultimately improves the effectiveness of a maintenance strategy. However, good management practices do not necessarily mean that the risk of failure is reduced nor that the availability of the plant is being improved (Cane, 2011).

Asset Maintenance Optimisation System (AMOS) focuses on the effectiveness of inspection and maintenance programmes. In this condition, skills for inspection, procedure and any quality must be developed. In AMOS, the first stage encompasses the benchmarking process and management audit whilst the second phase comes up with a plan for the application of risk-based inspection and maintenance and planning tools (Cane, 2011).

In trying to optimise maintenance strategies, maintenance personnel have to avoid carrying out imperfect maintenance strategies. According to Do *et al.* (2015), imperfect maintenance restores components to a condition between good as new and bad as old. As stated by Do *et al.* (2015), imperfect maintenance tasks are normally due to human errors and these arise from several factors such as stress, lack of skills and lack of attention. Other causes of imperfect maintenance are lack of spare parts and lack of time among many other things. Moreover, imperfect maintenance strategy accelerates the rate of deterioration of a system.

However, as is always the case, the implementation of perfect maintenance can be expensive. This leads to organisations employing imperfect maintenance to avoid or reduce high costs. Imperfect maintenance poses disadvantages such as:

1. The deterioration of the components after imperfect maintenance might not be reset to zero (good as new).
2. The imperfect maintenance might accelerate further deterioration (Kurt and Kharoufeh, 2010).

An example where imperfect maintenance can accelerate further deterioration is in welding. Welding can reduce the size of the crack; however, it may also destroy some physical behaviours of the material thus making it more susceptible to deterioration.

2.5 MAINTENANCE STRATEGIES SELECTION

The selection of a maintenance strategy for implementation is based on many factors such as tools, type of components, availability of skilled personnel, spare parts, applicability, safety, environmental problems, costs, mean time between failures, mean time to repair and managements' view. It also depends on the organisation's objectives. Different maintenance strategies are normally used for different components of the same system. Generally, in the selection of the maintenance strategy, the technical requirements must be combined with the organisation's strategy and it is normally difficult to combine the two (Bevilacqua and Braglia, 2000; Shafiee *et al.*, 2019).

Proper selection of a maintenance strategy, according to Shafiee *et al* (2019) can result in many benefits such as;

1. Reduction in the risk of fatal and/or costly damages;
2. Savings through reduced maintenance costs;
3. Increase in customer satisfaction;
4. Increase in product quality.

However, failure to select a suitable maintenance strategy, apart from resulting in the direct opposite of the benefits that have been mentioned, affects the systems' reliability, safety and availability. It is therefore important in a multi-criteria decision-making (MCDM) problem to evaluate all options, rank them to determine the best alternative, taking into consideration all aspects such as reliability, safety, availability, failure frequency, downtime, availability of skilled personnel and the availability of spare parts (Shafiee *et al.*, 2019).

In research done by Bevilacqua and Braglia (2000) to try and come up with a method of maintenance strategy selection which maintenance personnel can use, the Analytic Hierarchy Process (AHP) was used. AHP focuses mainly on repairability, reliability, cost, and availability. In their research Reliability-centred Maintenance (RCM) methodology was used. To categorise components on risk or reliability, failure modes of different components as well as other tools were used such as Failure Mode Effect and Criticality Analysis technique (FMECA).

In performing FMECA, Shafiee *et al.* (2019) went through several steps including the following:

1. Defining the system;
2. Listing the components/parts of the system (functional analysis);
3. Identifying all failure modes of the components or parts under consideration;
4. Performing a criticality analysis to evaluate the risk levels of each failure;
5. Ranking the failures concerning the criticality measure;
6. Taking action on the high-risk failures;
7. Checking the effectiveness of corrective actions and revising the risk analysis.

In performing the FMECA, one can use qualitative or quantitative data depending on which one is available and easily accessible.

However, the problem of defining the best maintenance strategy for each group remains difficult as the component's maintenance strategy should be in line with the component's failure mode, failure effects, failure cost, mean time to repair, mean time between failures among many other things associated with that specific component.

In studying an Italian oil refinery organisation, Bevilacqua and Braglia, (2000) looked at several factors to select a suitable maintenance strategy. These included:

1. Safety
2. Machine importance to the process
3. Maintenance costs
4. Failure frequency
5. Duration of downtime
6. Availability of spare components
7. Availability of spare parts

Based on the above factors, the components were divided into three groups. The maintenance strategy was then selected based on the group's characteristics. In cases where factors overlapped, AHP was used (Bevilacqua and Braglia, 2000).

AHP was used in three steps as follows:

Step 1: Decision definition through the hierarchy of objectives. Objectives that the organisation prioritises the most must be at the top whilst those that are lower in priority must be at the bottom.

Step 2: Weigh the criteria. In this case, AHP uses pairwise comparison to determine weights and ratings so that the analyst can concentrate on a few factors at a time. At this point, some factors are compared, such as a maintenance policy factor and the costs associated with it. Table 2.2 below shows how step 2 was done for the Italian oil refinery.

Table 2.2: Judgement score in AHP (adopted from Bevilacqua and Braglia (2000))

Judgement	**Explanation**	**Score**
Equally	Two attributes contribute equally to the upper-level criteria	1
Moderately	Experience and judgement slightly favour one attribute over another	2 3
Strongly	Experience and judgement strongly favour one attribute over another	4 5
Very strongly	An attribute is strongly favoured and its dominance demonstrated in practice	6 7
Extremely	The evidence favouring one attribute over another is of the highest possible order of affirmation	8 9

Step 3: After a judgement matrix has been developed, a priority vector to weigh the elements of the matrix is calculated. This is the normalised eigenvector of the matrix.

AHP is a multi-criteria decision technique and has some important aspects that make it applicable for this task and the process more credible. These are: the possibility to measure the consistency in the decision-maker's judgement; it guides the user in decision-making; the possibility of conducting a sensitivity analysis; it can integrate both quantitative and qualitative information; and it is supported by commercial software programs (Bevilacqua and Braglia, 2000).

After the three steps that have been mentioned, a hierarchy scheme is then formulated. The main aim of designing the AHP hierarchical tree is to come up with a framework that will meet the needs of the user in maintenance strategy selection. Therefore, the process starts by breaking down a complex, multicriteria problem into a hierarchy where each level comprises a few manageable elements that are then broken down into another set of elements.

Interpretive Structural Modelling (IMS) was used in the hierarchy structure. This tool helps in identifying and summarising relationships among different factors involved in the multicriteria decision-making process. The steps of IMS used in the analysis of the Italian oil company by Bevilacqua and Braglia (2000) are:

i. Identification of elements which are relevant to the decision-making problem.

ii. A contextually relevant subordinate relation is chosen.

iii. A structural self-interaction matrix (SSIM) is developed based on the pairwise comparison of elements.

iv. SSIM is converted into a reachability matrix and its transitivity is checked.

v. Once the transitivity has been achieved, the conversion of an object system into a well-defined matrix model is obtained.

vi. The partitioning of the elements and the extraction of the structural model termed ISM is then performed.

Some research, such as the one done by Shafiee *et al.* (2019) uses the Analytic Network Process (ANP) as well to select a maintenance strategy. In the study, ANP was combined with a cost risk criticality analysis model to select a cost-effective, low-risk maintenance strategy for different sets of components of a complex system.

In using ANP, the following steps are followed;

i. Select a system and all components under consideration. This is done so that all information relating to the system and components can be gathered. The information helps in determining the proper maintenance strategy.

ii. Determine alternative maintenance strategies for each component. Several maintenance strategies can be brought into the picture. In this instance of rolling stock maintenance, reactive, preventive and predictive maintenance are brought into the picture.

iii. Identify and classify selection criteria. This means that the organisation spells out what they deem necessary in a maintenance strategy, for example, an organisation in a maintenance strategy can value the costs associated with that maintenance strategy. Maintenance strategies differ in maintenance costs such as hardware, software, personnel training, tools, spare parts and software for data analysis. An organisation might also select a maintenance strategy from the criticality of failure point of view.

iv. Identify component interdependencies. There are three types of component interdependencies in a multi-component system and these are structural, stochastic and economic. Structural interdependence means maintenance of a failed component implies maintenance of other components in the multi-component system. Stochastic interdependence means the failure of a component can affect the condition of other components and economic implies that performing maintenance on a group of components is less costly and time-consuming than maintaining components one by one. A dependency analysis can focus on interdependency and also on order and level. Order of dependency will focus on whether it is a first-order or second-order or even higher dependency whereas level of dependency will focus on whether the dependency is partial or maximum.

v. Construct a network model. A network model is constructed with a goal, criteria, sub-criteria, and alternatives. Figure 2.15 shows a model that was used in the selection of a maintenance strategy for a marine renewable energy system. It illustrates a network structure of the ANP/CPN decision model applied to maintenance strategy selection and it includes three clusters. The first one is the main goal of the problem that is the selection of a cost-efficient and low-risk maintenance strategy. The second cluster consists of two main criteria which are cost and criticality. The last cluster represents alternative maintenance strategies.

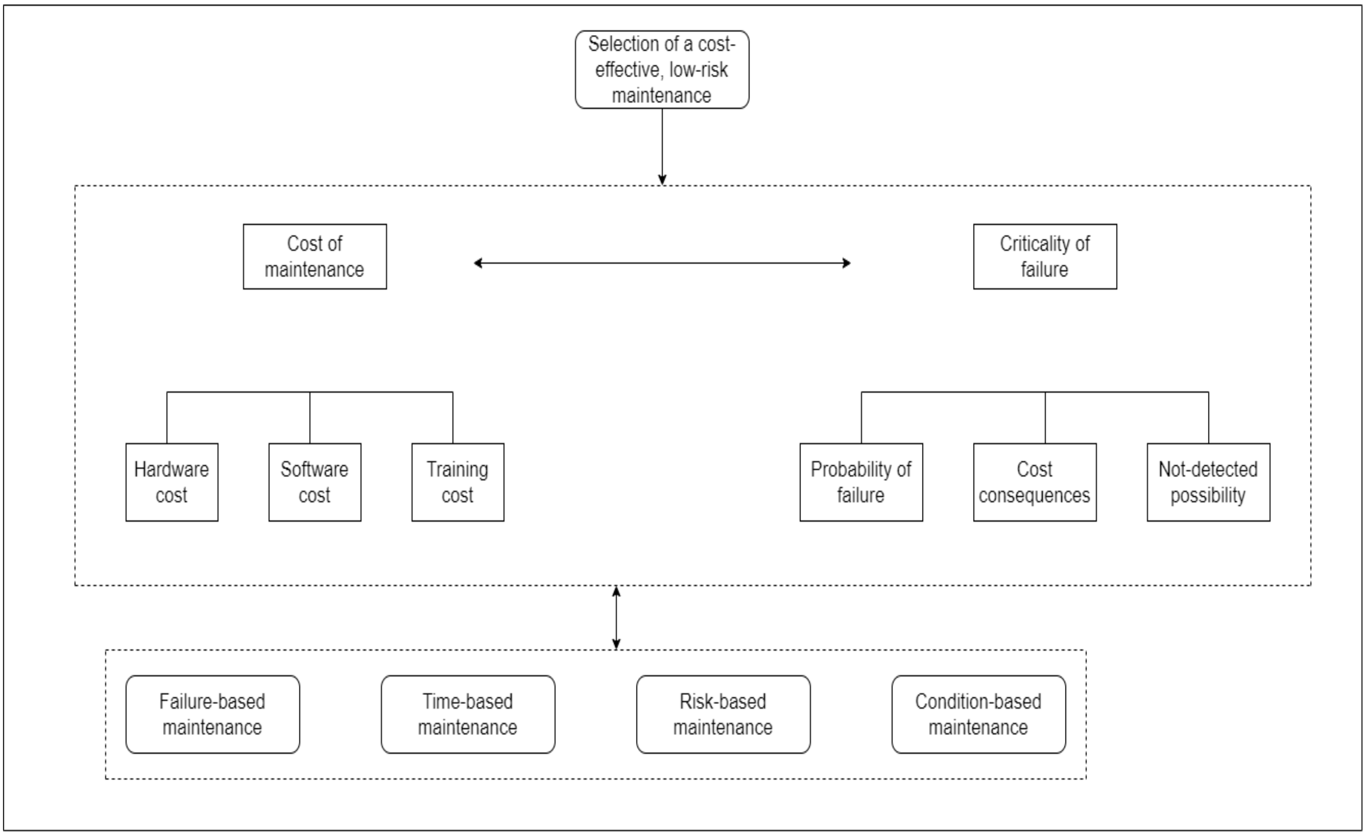

Figure 2.14: A network model for an MS selection (adopted from Shafiee et al. (2019))

vi. Perform pairwise comparisons of the decision elements. This is a useful tool for analysing some factors. Instead of going through them at once which might be tedious and very difficult to compare them, pairwise comparison helps in breaking down the problem to manageable units so that two factors can be analysed at a time. Results are then recorded as values, then, at the end, the values are summed up for each factor. In prioritising different maintenance strategies, pairwise between decision criteria and alternatives are usually performed by the maintenance personnel. In the study of the Italian oil company, the relative importance values are expressed using Saaty's 1-9 scale whereby 1 represents equal importance between two elements and 9 will represent the extreme importance of one element over the other. In coming up with a pairwise matrix, four sets of questions are asked which tend to unearth implementation costs, comparison data for sub-criteria, comparison of maintenance strategies based on sub-criteria comparison and finally sub-criteria are compared based on maintenance strategy alternatives.

vii. Calculate the priority vector for all the comparison matrices and test the consistency. Calculation of this vector is done by using

$$A \times W = \lambda_{max} \times W \qquad \textit{Equation 2.1}$$

Where

A – represents the pairwise comparison matrix

W – is the eigenvector

λ_{max} – the largest eigenvalue of A

In analysing the consistency of the comparison matrix of pairwise, the consistency ratio (CR) is used to identify possible errors.

$$CR = \frac{\lambda_{max} - n}{(n-1) \times RI} \qquad \textit{Equation 2.2}$$

Where

n- is the number of elements

R I- is average consistency index for numerous random entries of the same order reciprocal matrices

viii. Conduct ANP analysis. A super matrix is then used to represent the impact of elements on each other in a network. The super matrix is subdivided in such a way that each sub-matrix consists of priority vectors from the pairwise comparisons. The relationship of two categories in the super matrix is represented by columns and they reflect the influence the elements of the categories on the left-hand side of the matrix exert on those in the header of the matrix. In situations where there is no relationship between clusters, the corresponding entry in the super matrix becomes zero.

ix. Select the most appropriate maintenance strategy. At this stage, the desirability index is calculated. The desirability for maintenance strategy, i, is calculated as follows

$$D_i = \sum_{j=1}^{J} \sum_{k=1}^{K_j} C_j M_{kj} A_{ikj} \qquad \text{Equation 2.3}$$

Where

J – is the index set for criterion j

K_j – is the index set of sub-criterion j

C_j – is the relative importance of criterion j

M_{kj} – is the relative importance of sub-criterion k of criterion j

A_{ikj} – is the rating of alternative, i, on sub-criterion k of criterion j

The maintenance strategy with the highest desirability index is selected as the best maintenance strategy that should be adopted. In the proposed ANP model, the best alternative is the alternative with the highest value in its row of the limiting super matrix.

x. Feed results back into design, review and update the maintenance decisions regularly. The maintenance strategies need to be updated all the time as real-life application changes with time.

2.6 Chapter Summary

This chapter focused on reactive maintenance, preventive maintenance, predictive maintenance, maintenance strategy optimisation and maintenance strategy selection.

The factors that were looked into on maintenance strategies are scheduling, implementation (resources availability, level of skill, management commitment, the influence of other departments), data collection, failure rate and inspections (continuous, periodic, non-periodic).

On maintenance optimisation, factors such as benchmarking, assessing the condition of the plant, Asset Maintenance Optimisation System (AMOS) were detected whereas under maintenance strategy selection some factors to be used in selecting a maintenance strategy were discussed. These included tools, type of components, safety, availability of spare parts, mean time between failures, mean time to repair, environmental problems and availability of skilled personnel.

Factors that affect the proper implementation of maintenance strategies as summarised by (Singh, A. Gupta, *et al.*, 2016a; Phogat and Gupta, 2017) are shown in Figure 2.15. They are given as maintenance strategy implementation barriers.

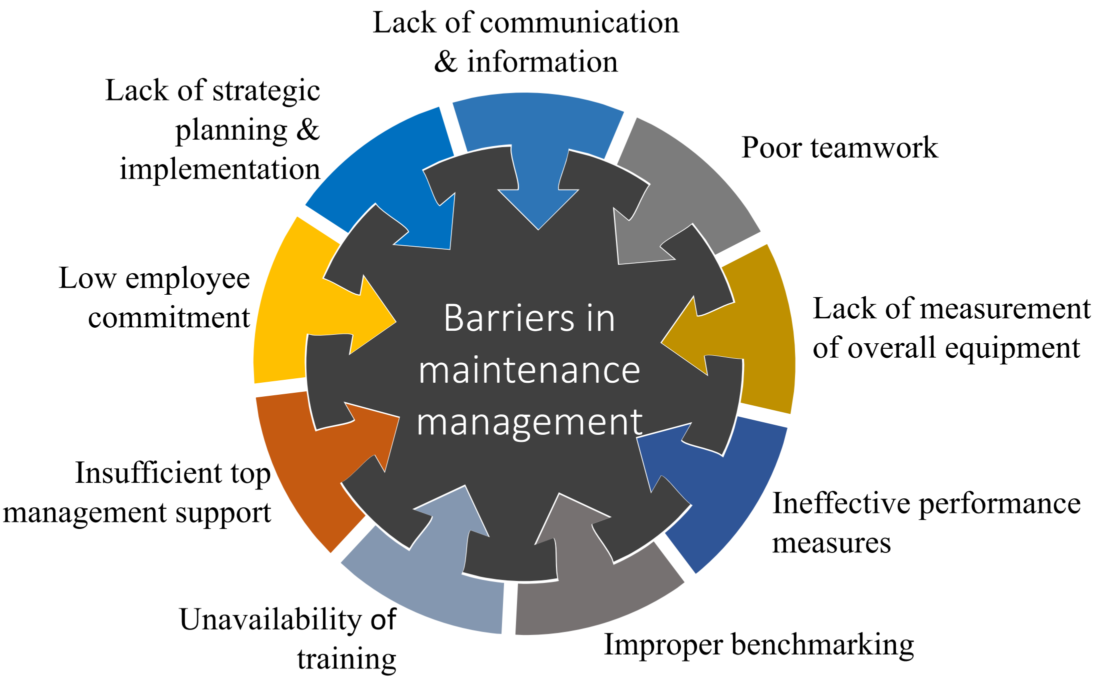

Figure 2.15: Barriers in maintenance management (adapted from Gupta et. al. (2017))

Raouf *et al.*, (2006) states that an effective maintenance strategy is one that fits the needs of business and its performance is measurable. Maintenance performance measurement can be done through measuring certain variables. These include human resource management, financial aspects, continuous improvement, maintenance approach, task planning and scheduling, policy deployment and organisation, carrying out maintenance, spare parts management, information management and CMMS and contracting out maintenance.

Chapter 3

MAINTENANCE PERFORMANCE MEASUREMENT

3.1 INTRODUCTION

Maintenance personnel and asset care managers need to know the contribution of maintenance to the business objective of the organisation (Parida *et al.*, 2015). Much work has been done on maintenance performance measurement. This was done to be able to see the role played by maintenance strategies in the organisation. Breakdowns and downtime have a huge impact on the performance of the plant. As stated by Raouf *et al.*, (2006), the effectiveness of a maintenance strategy can only be known if one can identify and evaluate a given maintenance strategy. According to Ku and Kim, (2019), performance measurement is a comparison of results with expected results. Organisations measure maintenance performance to remain competitive, identify existing gaps, indicate improvement and to run a cost-effective business (Aju kumar, Gupta and Gandhi, 2019; Wijesinghe and Mallawarachchi, 2019). Researchers such as Kang *et al.*, (2016) suggested the use of financial data as a measure of maintenance performance. In situations where operating costs remain high as well as maintenance costs then the maintenance strategy being implemented is not effective. However, the use of financial data alone is not efficient and is not a true reflection of maintenance performance. This then paves the way for the introduction of other measuring methods such as the use of balanced scorecards and smart systems (Kang *et al.*, 2016). The performance measurement system can include both financial and non-financial metrics as well as soft and hard metrics. Soft metrics include employee attitudes. The study of maintenance performance measurement has been great since it paves the way to prove that maintenance is not just a waste as some managers claim (Parida *et al.*, 2015).

However, Lundgren, Skoogh and Bokrantz, (2018) state that it is difficult to quantify maintenance strategy effectiveness; therefore, researchers have come up with many models and frameworks to quantify maintenance strategy effectiveness.

3.2 MAINTENANCE PERFORMANCE MEASUREMENT

Several performance maintenance measurements have been put forward by researchers. Some of the proposed ways of measurement are generic whereas some of them are specific to different industries such as the manufacturing industry, the energy industry and the aviation industry. According to Peach, Ellis and Visser, (2016), maintenance performance can focus on a variety of aspects such as equipment performance, cost performance, process performance and maintenance function.

Of note is the method proposed by Kang *et al.*, (2016), which states three categories that need to be established to effectively measure the performance of maintenance as presented in Figure 3.1.

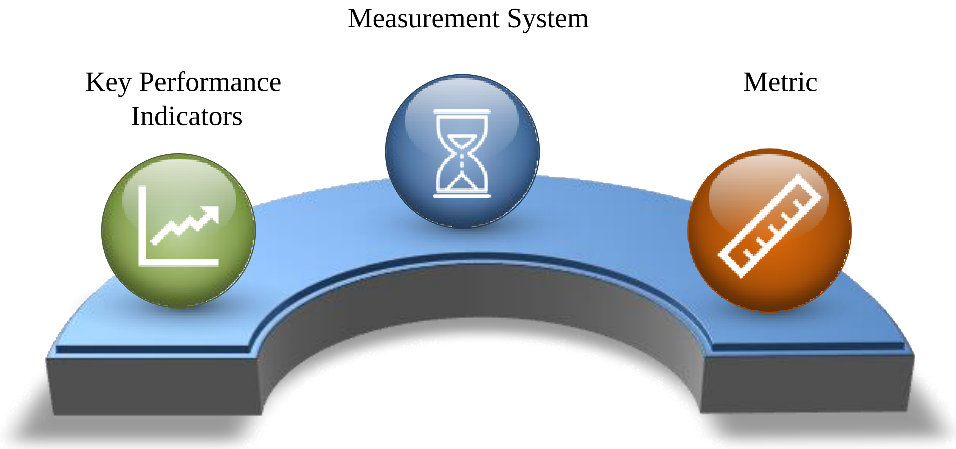

Figure 3.1: Three categories of performance measurement (adapted from Kang et.al. (2016))

According to Parida *et al.*, (2015), some researchers consider metric as the unit of measure. In this case, measure means specific observations characterising performance whereas performance indicator is a specifically defined variable.

However, application of these measuring models, frameworks, concepts and strategies is limited in the industry despite vast research on them. It remains difficult to quantify maintenance strategy effectiveness and this signifies a gap between research and practice (Lundgren, Skoogh and Bokrantz, 2018).

3.2.1 Measurement system

A measurement system can be defined as a set of metrics used to quantify the effectiveness and efficiency of actions (Parida *et al.*, 2015). These include the balanced scoreboard. According to Aju kumar, Gupta and Gandhi, (2019), measurement systems help in identifying and integrating four aspects namely financial, customer, internal business, and innovation. Before the advent of balanced scoreboards maintenance performance was based mainly on financial measurements. The maintenance measurement system has mainly been divided into two, namely models and frameworks. A framework helps in identifying boundaries, setting up dimensions and relationships among dimensions (Ku and Kim, 2019).

In the non-financial measure of performance, the focus when considering relationships is normally on quality, profitability, effectiveness, efficiency and survival for growth (Ku and Kim, 2019).

Peach, Ellis and Visser, (2016), proposed a maintenance performance measurement framework which included human aspects in the framework. These included knowledge, skills, abilities and personal characteristics which are known as elements of competence. Quality, efficiency, and effectiveness of maintenance work rely on the maintenance worker performing the maintenance activities. Phogat and Gupta, (2017), further emphasised the importance of the level of skill of personnel and the availability of resources. Human factors should never be ignored in maintenance performance measurement as they ensure safe, effective and efficient system performance.

3.2.1.1 Models

Lundgren, Skoogh and Bokrantz, (2018) came up with model categories. In these categories, models were grouped to form different categories based on what they are measuring. These categories are;

1. Economic value
2. Categorisation of maintenance losses
3. Cost and cost-effectiveness associated with maintenance activities
4. Overall management
5. Function oriented planning
6. Maintenance and simulation

Several models fall under these six categories as identified by Lundgren, Skoogh and Bokrantz, (2018).

1. Economic value

The models that fall under this category are of the economical type. The main focus is on costs, net present value or profitability. Under the economic value, four models were identified and these are;

a. Value-driven maintenance

This is a maintenance management model which seeks to add value and profit to the organisation. The identified value drivers in this model are utilisation, resource allocation, cost control, health and safety, and environment. In measuring the value added by these drivers, cash used in implementing them is added and the sum subtracted from the amount received by the organisation as a result of them.

b. Life cycle cost analysis (LCC)

This is a model that considers the overall life cycle cost of equipment. It calculates the costs from start-up to the time the equipment can no longer be used. The cost calculations are for money spent on different maintenance strategies hence it helps to evaluate which maintenance strategy is better. At times LCC includes whether maintenance should be outsourced or not. In the LCC model costs are analysed in two groups; namely, direct costs and indirect costs. This model is normally used in a stable market.

c. Life cycle profit (LCP)

This model is normally used in the manufacturing environment. It is used to estimate how much equipment can contribute to the profit of an organisation rather than trying to reduce the cost of maintenance in its life cycle as in the case of LCC. In the LCP model, the costs are divided into three groups namely direct costs, indirect costs and non-realised revenue. Non-realised revenue is the income that the organisation did not get as a result of low sales or low production due to maintenance issues. Under LCP one can assess how investment in different maintenance strategies can impact the business objectives of an organisation.

d. Sustainability statement

This economical model was developed by Sustainability Circle in Sweden. It was divided into four sections namely;

- Internalities that can be verified. These include sales, cost of sold goods and investments.
- Internalities that cannot be verified. These include efficiency and quality losses.
- Externalities that can be verified. These include the absence of environment and restored environment.
- Externalities that cannot be verified. These include personal and irreversible environmental damage.

Therefore, the Sustainability statement model can be used in analysing and accessing long-term decisions and investment in maintenance-related issues.

2. Categorisation of maintenance losses

The models that fall under this category describe different approaches to map the losses related to maintenance activities. These models provide ways of identifying maintenance losses in the system. Under categorisation of maintenance losses, there are three models:

a. Cost of poor maintenance (CoPM)

The model increases maintenance awareness among managers and employees. The aim is to identify areas which need improvement. It also evaluates the different areas where improvements have been implemented. To visualise the cost of a maintenance strategy being implemented, the model is divided into four categories namely;

i. Indispensable corrective maintenance;

ii. Valid preventive maintenance;

iii. Non-accepted corrective maintenance;

iv. Poor preventive maintenance.

Therefore, the model can be used to compare the cost of the weakness of different maintenance strategies to investments made on them.

b. Cost deployment

This model evaluates all losses in the hope of reducing their costs. In evaluating these losses in the manufacturing industry, the first step is to analyse production costs and categorise them. In analysing them, it is important to establish their relationships and the costs associated with each of them. On this model, one has to come up with ways of reducing these costs. Losses related to maintenance include breakdowns, short stoppages and reduced speed. The model can therefore be used to identify losses and to prioritise investments.

c. Waste reduction (related to maintenance)

To reduce maintenance waste, this model identified seven steps which are:

i. Requirements and needs investigation;

ii. Translating the needs to maintenance needs and tasks;

iii. Identify, group and measure waste related to maintenance;

iv. Develop solutions;

v. Estimate the economic value of solutions;

vi. Implement cost-effective solutions;

vii. Follow up on implemented solutions.

The model can be used to identify possible investment areas. Most importantly it gives room for follow-up and can result in huge waste reduction if done properly.

3. Cost and cost-effectiveness associated with maintenance activities

In this category, the focus is on cost-effectiveness on maintenance issues. The models aim to assess the changes suggested in a system. This category has ten models and these are:

a. Total quality maintenance (TQMain)

This model is based on the plan-do-check-act cycle (PDCA) which is used in total quality management (TQM). The use of PDCA on TQM helps in technical and managerial improvement systems. TQMain covers inspections, condition maintenance to utilise equipment during working hours and schedule preventive maintenance after working hours. Overall equipment effectiveness can be used as a measure for this model and the model can be used to evaluate different investments concerning overall process effectiveness (OPE).

b. Model to describe and quantify the impact of vibration-based maintenance

At the operations level of this model, it considers the investments on the technical impact and financial aspects. In making the investments the organisation considers how the technical aspects will influence the savings account such as fewer failures, fewer stoppages both long and short and higher quality rate.

c. A computerised model to enhance the cost-effectiveness of production and maintenance dynamic decisions

This model is used to identify, assess and control the time lost in production as well as evaluating the maintenance changes that have been put in place to see how they impact the production system. The losses in time at both strategic and technical levels must be documented before a maintenance change is implemented as well as afterwards, to have a clear view of the impact of the maintenance changes on these production times.

d. Maintenance function deployment (MFD)

This model identifies and quantifies the losses of an organisation. Under the model, the first step is to identify the outputs. In identifying the outputs, it should be clearly stated what should be delivered to keep the organisation in business and what should be maintained to achieve strategic goals. In evaluating the investment in different maintenance strategies and how they contribute to the strategic goals of an organisation, effects and actions associated with each maintenance strategy much be properly analysed.

e. CA-Failure

This is a model that uses the failure database of an organisation to prioritise failures, evaluate economic losses due to them and the impact they have on a competitive advantage. Under this model, each failure is analysed as well as its impact on the economic losses. When all the failures have been analysed, a Pareto chart is used for failure prioritisation. The final step is to assess the cost actions as well as the investment in a maintenance strategy to be implemented to prevent these failures from occurring again. To select the most profitable maintenance strategy, the investment needed to stop failures from occurring is compared to losses due to the failures that have happened.

f. Fuzzy multiple criteria decision-making model

This model is used to select the most efficient and cost-effective maintenance strategy. Under this model, it is important to start by coming up with failure causes which are a threat to a piece of equipment's life. Afterwards, through the use of fuzzy inference system and simple additive weighting, different maintenance strategies are ranked based on their ability to eliminate the causes of failure. The model can also be used in weighting investments concerning cost-effectiveness.

g. Activity-based costing (ABC) for cost estimation

This model is used to estimate maintenance costs. The overhead costs are put where they emanate from. This helps in analysing which part contributes to more overhead costs. The model can be used in assessing the maintenance strategies with associated overhead costs as well as the investments made.

h. Cost-effective degradation based maintenance

This model evaluates the relationship of degradation reduction of preventive maintenance actions and the costs associated with such actions. This model aims to find an ideal time for implementing actions under condition-based maintenance concerning the costs associated. It is one of the models that can be used to plan when implementing corrective maintenance.

i. Probability distribution of maintenance costs

This model as indicated by its name, gives a probability distribution of maintenance costs. It evaluates condition-based maintenance where the system uses stochastic gamma degradation. The model can be used in assessing maintenance investments as well as planning different maintenance tasks.

j. Cost model for maintenance services

This model is used in performance measurement as well as for making decisions on maintenance such as on service pricing, contract negotiations and outsourcing decisions. The model is therefore divided into different cost categories namely;

i. Operating costs

ii. Cost of machines

iii. Costs of logistics

iv. Spare parts cost

In all the above-mentioned costs, the total costs of the service provider and those of the customer are calculated so that it is easy to clearly state the savings of the customer as well as the profit of the service provider.

4. Overall management

The models in this category provide guidelines on how to work with maintenance management. The main objective of these models is to plan and control maintenance activities. Under this category there are two models, namely:

a. Total productive maintenance

This type of model has its focus on improving the effectiveness of maintenance. Through overall equipment effectiveness (OEE) it maximises the effectiveness of equipment. The main objective of TQM is to minimise six big losses which are;

i. Breakdowns

ii. Setup and adjustment time losses

iii. Idling and minor stoppages of the equipment

iv. Speed reduction for operation

v. Defect and rework losses

vi. Start-up losses

In making an investment decision, OEE can be used as a tool to evaluate the appropriateness of the investment.

b. The Eindhoven University of technology model

The model describes maintenance sub-functions and under the maintenance management function, it has 14 subsections. Major decisions and actions under each subsection are clearly stated. The tasks that are included in this model are;

i. LCCs

ii. Failure mode

iii. Effects and criticality analysis

iv. Cost calculations of waiting time for spare parts

v. Degree of centralisation

vi. Outsourcing

5. Function-oriented planning

Models included in this category are related to the function and reliability of the maintenance system. The focus is on evaluating the different type of failures among other things. Under this model there are four models namely:

a. Reliability-centred maintenance (RCM)

RCM focuses on the functions of a system. It does so by taking a planning approach for maintenance activities. It is largely divided into four parts namely:

i. Preserving functions

ii. Identifying failure modes that can disrupt functions

iii. Prioritising the functions

iv. Select effective preventive maintenance tasks according to it

This model can be used to rank and prioritise failures that need to be designed out.

b. Terotechnology model

This model is a link between management and financial engineering. It incorporates a feedback loop. With the feedback loop, it helps in designing out.

c. Kelly's Philosophy

In this model, maintenance is taken as a method of controlling reliability. Kelly came up with a ten-point plan in which firstly one has to define the functions of maintenance systems. To come up with a strategy, the objectives of the model should be spelt out.

d. Risk-based maintenance

The model is based on the following questions;

i. What can cause system failure?

ii. How can it cause the system to fail?

iii. What should be the consequences if it fails?

iv. How often can it occur?

v. Frequency of inspection on components that can cause such failures?

6. Simulation and maintenance

It focuses on planning and scheduling preventive and corrective maintenance strategies. It focuses on evaluating the impact of different maintenance strategies on production. This category has one model.

i. Simulation and maintenance

The model focuses on preventive maintenance and corrective maintenance, their impact on resource allocation, performance and costs. The model can be used to assess the long term effects of investment.

3.2.1.2 Frameworks

Through literature review, Parida *et al.*, (2015), identified 27 frameworks and these are summarised in Table 3.1 below.

Table 3.1: Maintenance measuring frameworks/models (adapted from Parida et al (2015)).

Model/ Framework	Measures/ Indicators/Criteria
Sink and Tuttle (1989)	Efficiency, effectiveness, quality, productivity, quality of life and innovation, profitability/budget ability, excellence, survival and growth
Du Pont Pyramid	Financial ratios
PM matrix	Cost factors, non-cost factors, external factors and internal factors

Results and determinants matrix	Financial performance, competitiveness, quality, flexibility, resource utilisation, innovation
PM Questionnaire	Strategies, actions and measures are assessed, the extent to which they support? Data analysis as per management position or function, range of response and level of disagreement
Brown’s framework	Input measures, process measures, output measures, outcome measures
SMART pyramid (Performance pyramid)	Quality, delivery, process time, cost, customer satisfaction, flexibility, productivity, marketing measures, financial measures
Balanced Scoreboard (BSC)	Financial, customer, internal processes, learning and growth
Consistent PM system	Derived from strategy, continuous improvement, fast and accurate feedback, explicit purpose, relevancy
PM frameworks for small businesses	Flexibility, timeliness, quality, finance, customer satisfaction, human factors
Cambridge PM process	Quality, flexibility, timeliness, finance, customer satisfaction, human factors
Integrated dynamic PM system	Timeliness, finance, customer satisfaction, human factors, quality, flexibility
Integrated PM framework	Quality, flexibility, timeliness, finance, customer satisfaction
Dynamic PM systems	External and internal monitoring system, review system, internal deployment system, IT platform needs
Integrated measurement model	Customer satisfaction, human factors, quality, flexibility, timeliness, finance
Comparative business scoreboard	Stakeholder value, delighting the stakeholder, organisational learning, process excellence
Skandia navigator	Financial focus, customer focus, human focus, process focus, renewal and development focus
Balanced IT Scorecards (BITS)	Financial perspective, customer satisfaction, internal process, infrastructure and innovation, people’s perspective

BSC of advanced information. Services Inc (AISBSC)	Financial perspective, customer perspective, people, infrastructure and innovation
Intangible Asset Monitor (IAM)	Internal structure: growth, renewal, efficiency, stability, risks (concept models, computers, administrative system). External structure: customer, supplier, brand names, trademark and image Individual competence: skills, education, experience, values, social skill
QUEST	Quality, economic, social and technical factors
European Foundation for Quality Management (EFQM)	Leadership, enablers: people management, policy and strategy, resources, processes Results: people and customer satisfaction, impact on society, and business results
EN 15341	Maintenance key performance indicators
Multicriteria hierarchical framework for MPM	Balanced and considering the strategic, tactical and operational perspective
Link and effect model	Technical indicators like availability, capacity utilisation, etc. at the operational level are linked to a strategic level through the tactical level and vice versa
Venezuela Norma Covenin	Manual for evaluation of maintenance systems through questionnaire and scoresheets
Integrated PM system	Finance, customer satisfaction, human factors, quality, flexibility, timeliness

3.2.2 Key performance indicators (KPI)

According to Aju kumar, Gupta and Gandhi, (2019), maintenance performance first needs the identification of indicators. Performance indicators highlight the deficiencies in an organisation and help to reach the root cause (Parida *et al.*, 2015). In the manufacturing industry, KPIs are a set of variables that are used to reflect operation performance. KPIs are used to evaluate the effectiveness of a carried out activity and the best way is to come up with KPIs that are specific to the organisation in consideration (Ku and Kim, 2019). Examples of KPIs are efficiency, throughput, availability, productivity and quality of products. Therefore, KPIs are a set of quantifiable variables within a maintenance measurement system that reflect the performance of an organisation (Kang *et al.*, 2016; Aju kumar, Gupta and Gandhi, 2019).

However, it is very difficult to measure everything associated with maintenance. It is therefore important to select what is considered critical in meeting the objectives of the organisation. An example is in the manufacturing industry where being able to meet production goals can be deemed as critical. Therefore, in such a case, measuring availability will be most ideal (Aju kumar, Gupta and Gandhi, 2019).

The European standard BS EN:15341 (2007) for KPI for maintenance performance provides three categories of indicators, namely; economic, technical and organisational (Aju kumar, Gupta and Gandhi, 2019).

Researchers have used performance indicators to measure the effectiveness of maintenance as well as to compare actual conditions with a specific set of reference conditions (Aju kumar, Gupta and Gandhi, 2019). Researchers have also argued the importance of analysing the relationship of different KPIs. This is because KPIs affect one another; therefore, it is important to know which one influences the other. Some of the KPIs identified by Aju kumar, Gupta and Gandhi, (2019), Ku and Kim, (2019) are customer satisfaction, cost, equipment, maintenance safety and environment, employee satisfaction, downtime, change over time, planned maintenance tasks, unplanned tasks, number of new ideas generated, skill, number of training, failure rate, equipment availability, and improvement training, quality returned and employee complaints.

Metrics for maintenance performance are important in an industry as they help to come up with corrective action and guiding steps to meet organisational objectives. According to Wijesinghe and Mallawarachchi, (2019), availability of spare parts and how often they are purchased can be used as a measure for maintenance performance as well as calculating the amount that is being spent on maintenance.

According to Parida *et al.*, (2015), performance indicators can be divided into categories, namely economic, technical, equipment performance (availability, reliability), cost performance (maintenance, labour and material cost) and progress performance (ratio of planned and unplanned work, schedule compliance).

In analysing key performance indicators (KPIs), Aju kumar, Gupta and Gandhi, (2019), came up with a list of maintenance goals, maintenance functions as well as the key performance indicators associated with them.

3.3 CHAPTER SUMMARY

The chapter analysed the measurement systems that have been proposed by different researchers. The measurement systems can either focus on financial or non-financial measurements. Maintenance performance measurement can focus on different aspects such as equipment performance, cost performance and process performance. The metric that is used in the maintenance measurement system includes employee attitude, quality, efficiency, profitability, effectiveness, knowledge, skills, abilities, competency, level of skills, availability of resources, utilisation, resource allocation, cost control, health and safety and environment, maintenance losses, breakdowns, short stoppages and operating costs.

Chapter 4

RESEARCH METHODOLOGY

4.1 INTRODUCTION

Research methodology can be defined as a philosophical framework used in conducting research or can be stated in other words as the foundation on which research is based (Saunders, Lewis and Thornhill, 2009). When doing research, a research methodology is used to describe and explain how the research was done. It is used to qualify the decisions taken throughout the research to arrive at the results and putting into context the research at hand. The research design of this study was adopted from Saunders, Lewis and Thornhill (2007). In following the research design adopted, Figure 4.1 shows what was incorporated into the research. These included research techniques and procedures, the time horizon of the study, research strategies, research philosophies and research approaches.

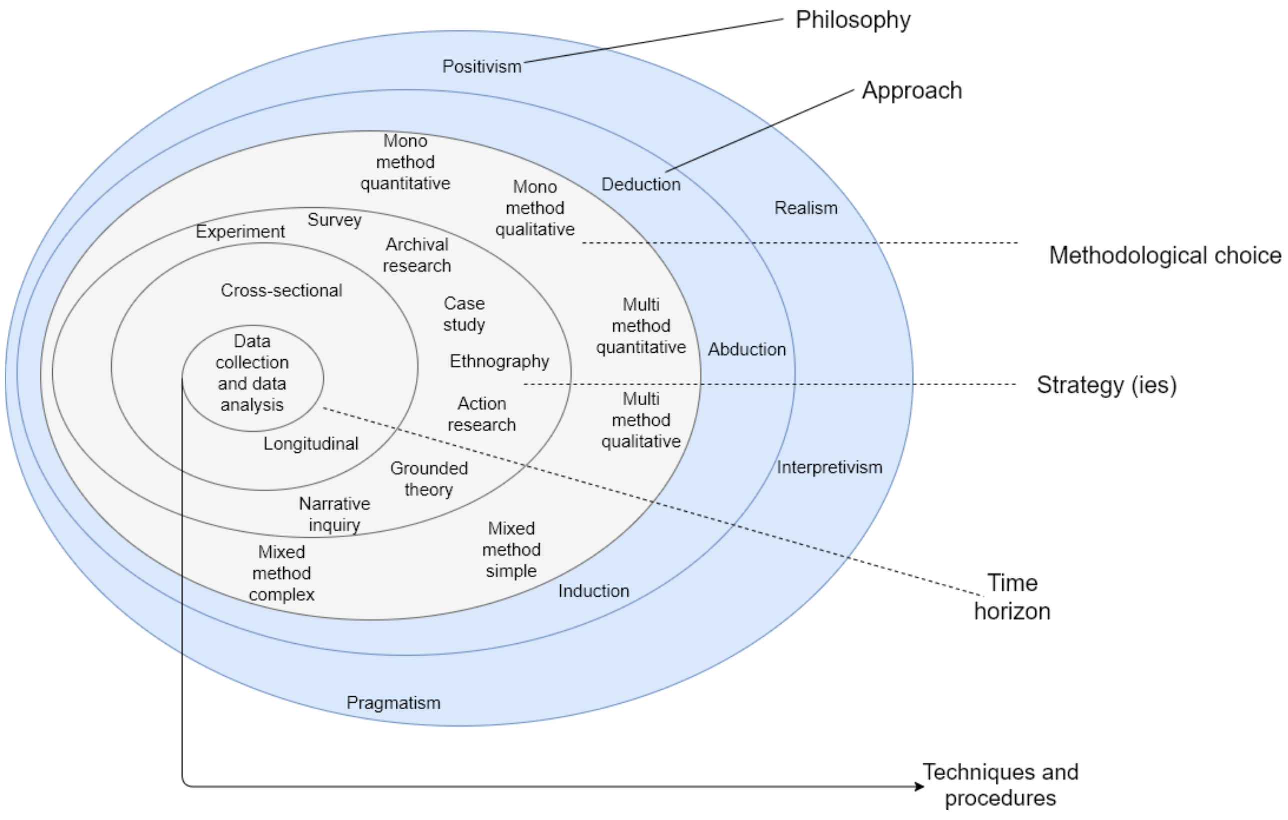

Figure 4.1: Research Onion (adapted from Saunders et.al. (2012))

4.2 RESEARCH PHILOSOPHY

As shown in Figure 4.1, the research onion has different layers, namely the research philosophy, research approach, research methods, research strategies, time horizon and research techniques and procedures. Each layer of the onion can be explained as follows;

Research philosophy – According to Saunders et al (2009) this layer consists of positivism, realism, interpretivism and pragmatism. This is the outer layer of the research onion. However, the main research philosophies are pragmatism, positivism and interpretivism.

Positivism – This is a philosophy which emphasises the need to use natural science methods when studying social reality since in such scenarios senses can be used for observation and verification. Positivism can also be used as a deductive or inductive research approach. However, this philosophy can only be used for quantitative analysis and it is objective which is positive since it will not be dependent on the instincts of the researcher.

Pragmatism – A system can be analysed and interpreted in many ways by using pragmatism philosophy. Research can be done in many different ways to paint a proper picture of reality. This philosophy can be deductive or inductive and it can also be qualitative and or quantitative. The philosophy can be subjective or objective as well. The research question is more often used in determining the research philosophy.

Interpretivism – This approach needs the researcher to fully understand and be able to interpret the subject at hand through social tools such as language. It can only be used in inductive research and where qualitative analysis is done. However, the approach is subjective and can also be biased.

This study adopted pragmatism, because from the three approaches, it is the only approach that is both deductive and inductive as well subjective and or objective and neither interpretivism nor positivism possesses that characteristic (Saunders, Lewis and Thornhill, 2007). Therefore, the pragmatism approach has more advantages over the other two philosophies.

When using the pragmatism philosophy, research questions provide guidelines to the research as such proper formulation of the research questions cannot be overemphasised.

4.3 RESEARCH APPROACH

The research approach has a huge influence on research methods and should be prioritised in research methodology (Saunders, Lewis and Thornhill, 2009). The research approach can be either deductive or inductive. When a researcher comes up with a hypothesis or conclusion based on available literature then the research is deductive whereas according to Bryman *et al.*, (2014) if the researcher subjects literature findings to empirical analysis then it is regarded as inductive research (Wilson, 2010). As stated by Gulati, (2009), in the deductive approach the researcher tests the relationship or link between theory and data if it exists. When performing an inductive approach, researchers have to collect data, analyse it and develop a theory. At the end of the process (data collection and analysis) the theory is then proposed (Goddard and Melville, 2004). In a nutshell, in testing the validity of assumptions such as theories and hypothesis, the deductive approach is used whilst the inductive approach is used to propose new theories and generalisations (J Dudovskiy, 2018).

An inductive approach was utilised in this study since the research sought to explore different strategies used in maintenance and their influence on the availability of rolling stock and also to develop a conceptual framework that can be used to implement a maintenance strategy.

4.4 Research Strategy

Researchers use different research strategies depending on the research being carried out as each strategy can be used for exploratory, descriptive and explanatory research (Yin, 2009). Normally, in determining the strategy to use, the researchers focus on their research questions, objectives, timeline and other resource availability for guidance (Saunders, Lewis and Thornhill, 2007). Appendix A shows the different research strategies which include qualitative research, quantitative research and mixed-methods research (Bryman *et al.*, 2014).

Quantitative research is a numerical type of research because it mainly focuses on figures. The major aim of quantitative research is to find evidence that will help to support or reject the hypothesis at hand. The qualitative approach is non-numeric, the information can be collected through text documents, interviews, images and video recordings (Dudovskiy, 2018). Therefore, when conducting a qualitative study the researcher is concerned about non-statistical methods, small samples that are often purposively selected whereas in a quantitative study the researcher focuses on testing a given theory which is composed of some variables which are numerically measured and analysed with statistical procedures to determine the validity of a theory (Vos, Strydom and Delport, 2012).

Qualitative research is concerned with answering the ‘why’ and ‘how’ questions. Some consider qualitative as a subjective way of researching, hard to follow and at times not transparent as it is based on the researcher’s views. At times it is difficult to understand decisions taken by the researcher, for example, in interviewing, it is hard to understand the criteria used to choose people, how people are chosen for observations and the final analyses of data and its conclusions.

Normally, due to the presence of numerical values, the quantitative approach is associated with both high precision and accuracy. When conducting quantitative research, an assumption that respondents interpret questions the same way is made; however, in reality, this is not true. Heavy reliance on instruments in data collection and analysis also poses a risk as these instruments might be faulty (Bryman *et al.*, 2014). However, qualitative and quantitative studies are not mutually exclusive as researchers often combine the two in what is called a mixed research approach (Vos, Strydom and Delport, 2012).

Since quantitative and qualitative approach can be used together in one piece of research, mixed methods research strategy is used in this research to capitalise on the strengths of both approaches and offset their demerits. Mixed methods strategy involves collecting and analysing quantitative and qualitative data (Vos, Strydom and Delport, 2012).

4.5 RESEARCH METHODS

Saunders, Lewis and Thornhill (2007) defined research methods as techniques and procedures that are used in data collection and analysis. The research methods comprise of data collection and analysis techniques, namely mono-method, mixed-method and multi-method (Dudovskiy, 2018). When using a mono-method, a researcher uses a single data collection technique and corresponding analysis procedures. However, when the researcher uses more than one data collection technique and analysis procedure to answer the research question, it is called multi-methods approach while in a mixed-method approach, both quantitative and qualitative data collection techniques and analysis procedures are used (Saunders, Lewis and Thornhill, 2007). In this research, the mixed-method approach is used. These methods include interviews, historical data and case studies. Research methods that are used in this study include interviews, case studies and archival research. In-depth semi-structured interviews were used to validate the research outcome. Subject matter expert opinion was sought through telephonic and Microsoft teams in-depth interviews.

Interviews are a conversation between the researcher and the interviewee. The interviewer asks participants questions to gather data about their opinions, beliefs, views and ideas. Interview questions can be open-ended, semi-structured or structured (Maree, 2012). During interviews, rich descriptive data can be collected that can help the interviewer to understand the participant’s knowledge and social reality (Bryman *et al.*, 2014). For interviews to be an effective method, the researcher has to maintain neutrality, determine the type of interview to be done (be it structured, unstructured or focus groups) and prepare for the interview

In coming up with a questionnaire, three steps should be followed, namely creating a conceptual model (from analysis and synthesis of literature), produce the questionnaire (come up with informed consent, questions and response format needed) and finally pre-test the questionnaire.

The most important thing about questionnaires is that they maintain anonymity. However, to be effective, the researcher has to decide on the type of questions that will easily give the needed information (closed-ended are easier to analyse), maintain neutrality, be brief and focused, consider the respondent's literacy level, use a logical and justified sequence, use branching to avoid the reading of irrelevant material by respondents, make a clear layout and not offend respondents.

Archival research is when the investigation is done using historical material which can either be written material, multimedia or oral. The aim of using this method is normally to reveal patterns within a system. One needs a good methodological framework to analyse archival material. The analysis is, however, biased as it is dependent on the researcher.

In-depth interviews were used to get the input of subject experts. It helped to validate the output of the research and to make a meaningful contribution based on their contribution.

Case studies are normally used in explanatory and exploratory research. They involve an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence. The case study approach allows the investigator to retain the holistic and meaningful characteristics of real-life events such as organisational processes and group behaviour (Yin, 2009).

Case studies are done to give substantive data that will enable generalisation from the researcher. When doing a case study, the researcher needs to ask multiple questions and define the reference frame. Much data can be gathered through interviews, archival, direct observation and participant observation.

4.6 Data Collection And Analysis

Data collection is a process that involves the gathering of information from relevant information sources. This is done to answer research questions and to evaluate the outcomes (Dudovskiy, 2018). This study made use of primary and secondary data collection methods. The primary data collection methods included qualitative data collection. The data collection methods that were used were interviews and case studies. Purposive sampling was used in identifying and selecting participants for interviews. This is because the research needed to be validated by people with knowledge and experience. Purposive sampling is a non-probability sampling method that is most relevant when one needs to collect practical data on a certain domain from experts (Tongco, 2007).

The secondary data collection methods that were used included literature reviews. Systematic Literature Review (SLR) method was used since it is an evidence-based process. Systematic Literature Review is intended to evaluate all published literature on the topic. The method makes it easy to follow what the researcher did and it is transparent. A systematic literature review minimises bias from the researcher (Jackson, 2004; Petticrew *et al.*, 2006; Keele and Staffs, 2007; Bryman *et al.*, 2014)**.** The systematic literature review is a systematic way used to collect, integrate, evaluate critically and present findings from multiple research studies on a research topic. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) is used to ensure the proper method of review is followed. The PRISMA methodology addresses quality issues, such as bias, replicability and credibility and offers a broader and more accurate level of understanding than a traditional literature review. SLRs rely on standardised methodologies in searching, filtering, reviewing, critiquing, interpreting, synthesising, and reporting of findings from multiple publications on a topic of interest (Debajyoti et al., 2018). SLR follows clearly defined steps such as question formulation, identification of search domains and publication sources, systematic search, systematic critical analysis, systematic interpretation, and systematic reporting, as shown in Table 4.1 and Figure 4.2. One of the limitations of systematic literature reviews stems from situations where research questions cannot be defined in terms of the effect of a particular variable, or when the subject boundaries are more fluid and open or subject to change. Hence the systematic approach requires articles to be evaluated in terms of clear methodological criteria (Bryman *et al.*, 2014)

Table 4.1: Steps in the systematic literature review

Reference	**Proposed stages of Conducting a Systematic Literature Review**	**Objectives**
Bryman et al., (2014)	Planning the review	Specifying the research question (s)
	Conducting the review	Keywords and search terms
		Data analysis of what is known about the subject
	Reporting and dissemination	Identify contributors to the main research

		Where are the contributors based
		When was the main research activity conducted
		Define criteria for reporting study accessibility and readability
Debajyoti et al., (2018)	Planning the review	Develop your study question
	Data collection	Identify concepts to be included in your search
		Select databases relevant to your topic area to conduct your research
		Keywords to be used for the search
	Data selection	Decide the inclusion and exclusion criteria (PRISMA flow chart)
		You can also use snowballing
	Data analysis	A critical review of full articles

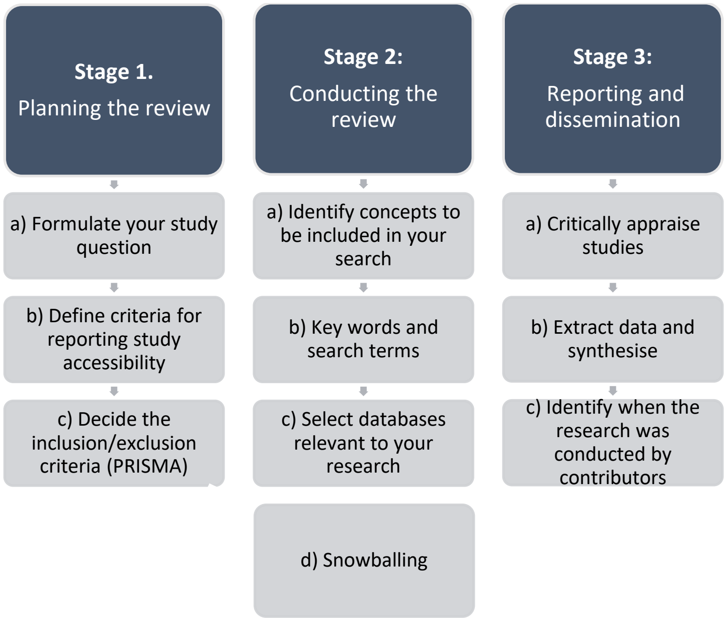

Figure 4.2: Methodology for conducting a systematic literature review

The main research question for this study was,

"*What is the influence of different maintenance strategies on the availability of rolling stock?*"

In coming up with the inclusion/exclusion criteria for systematic review, PRISMA was used (Debajyoti et al., 2018). The search was also confined to scientific journals, conference proceedings, technical reports, and textbooks.

A Systematic Review Protocol as shown in Figure 4.3, was developed to create keywords and build search strings. Boolean logic, wild cards and truncations were used to broaden the search options of the search strings. Each search string was developed by combining the search elements representing an objective using "AND". Each term in the string is linked to its synonyms using "OR". Table 4.2 shows a detailed list of search strings. The search is further refined by combining all the search strings per objective using "AND" to make the overall search string.

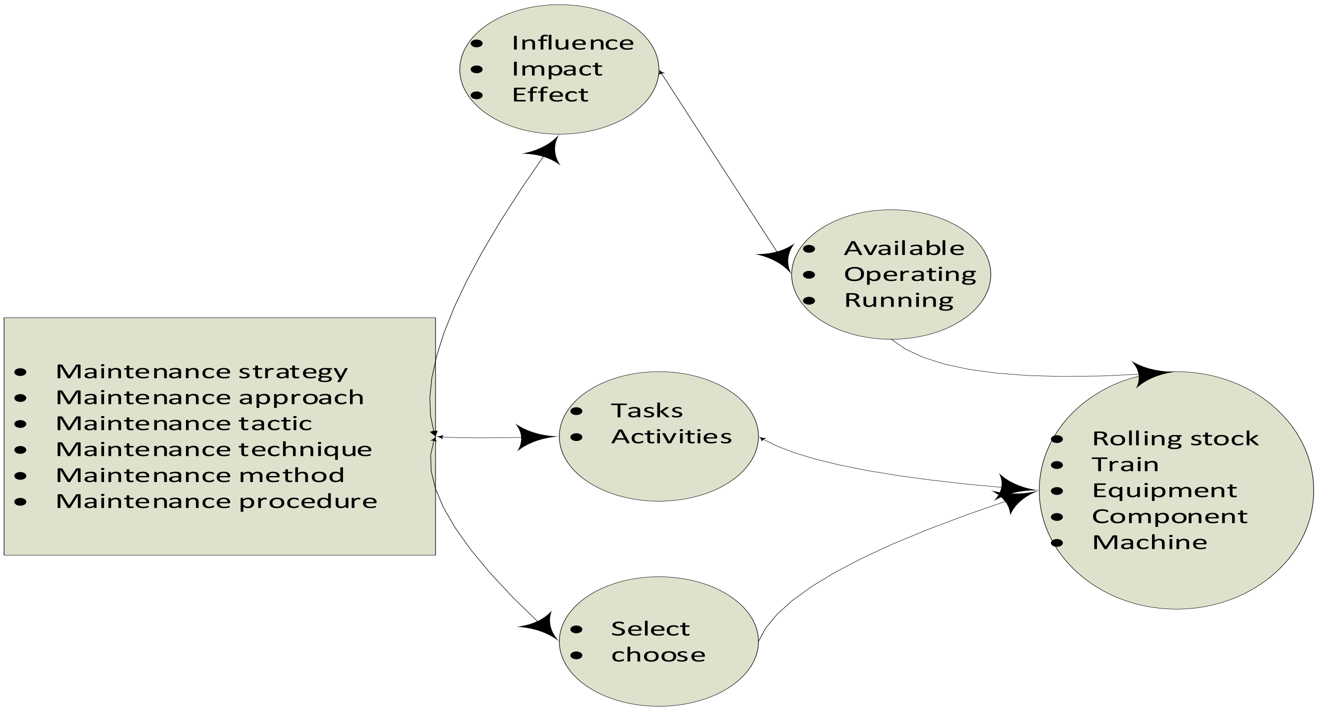

Figure 4.3: Systematic Review Protocol (SRP)

Table 4.2: Inclusion criteria

Search terms	Maintenance strategy, maintenance approach, maintenance tactic, maintenance technique, maintenance method, maintenance procedure, task, activity, selection, choose, available, operate, run, rolling stock, train, equipment, component, machine
Search strings	1. ("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance technique*" OR "maintenance method*" OR "maintenance procedure*") AND ("influence*" OR "impact*" OR "effect*") AND ("available*" OR "operate*" OR "run*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*") 2. ("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance technique*" OR "maintenance method*" OR "maintenance procedure*") AND ("task*" OR "activity*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*") 3. ("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance technique*" OR

	"maintenance method*" OR "maintenance procedure*") AND ("select*" OR choose*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*")
Period	2000 to 2020
Restrictions	Peer-reviewed academic journals, conference articles, book sections
Search fields	Title, Abstract, Keywords
Subject area	Engineering
Language	English

Table 4.3 shows the search terms that were used and the initial search results. Three data sources were used and these are Scopus, Web of Science and Emerald.

Table 4.3: Initial search results

	Search String	Scopus	Web of science	Emerald
#1	("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance technique*" OR "maintenance method*" OR "maintenance procedure*") AND ("influence*" OR "impact*" OR "effect*") AND ("available*" OR "operate*" OR "run*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*")	213	111	500
#2	("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance technique*" OR "maintenance method*" OR "maintenance procedure*") AND ("task*" OR "activity*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*")	544	138	500
#3	("maintenance strategy*" OR "maintenance approach*" OR "maintenance tactic*" OR "maintenance	320	178	500

	technique*" OR "maintenance method*" OR "maintenance procedure*") AND ("select*" OR choose*") AND ("rolling stock" OR "train*" OR "equipment*" OR "component*" OR "machine*")			

After the initial search from the three databases, studies were included for review based on the relevance of the topic. Secondly, selection for inclusion was based on the convenience and accessibility of the papers. Thirdly, the inclusion of papers for the SLR was based on the language used in the paper and lastly the relevance of the abstracts. Furthermore, after reading the abstracts of these papers, the snowball strategy was used to identify more papers to add to the total number of papers for the SLR. The result was a final dataset that was analysed using Qualitative Content Analysis (QCA) to extract themes and concepts. Figure 4.4 describes the PRISMA flow diagram for this study.

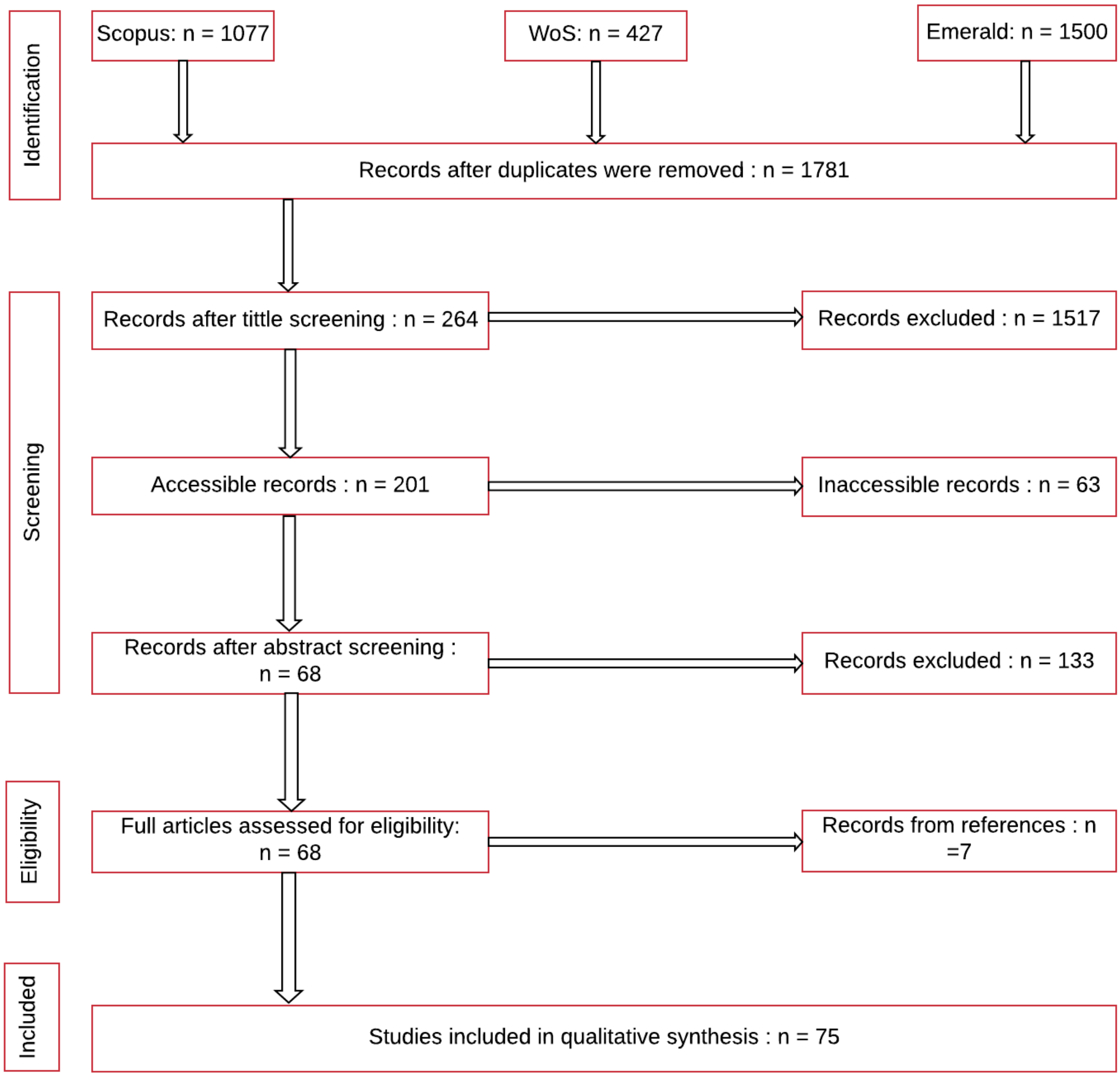

Figure 4.4: PRISMA flow diagram

The studies that were used in the research are classified in Appendix B. The studies were classified in terms of type of publication. Appendix B shows the type of publication and the number of papers that were used in this study.

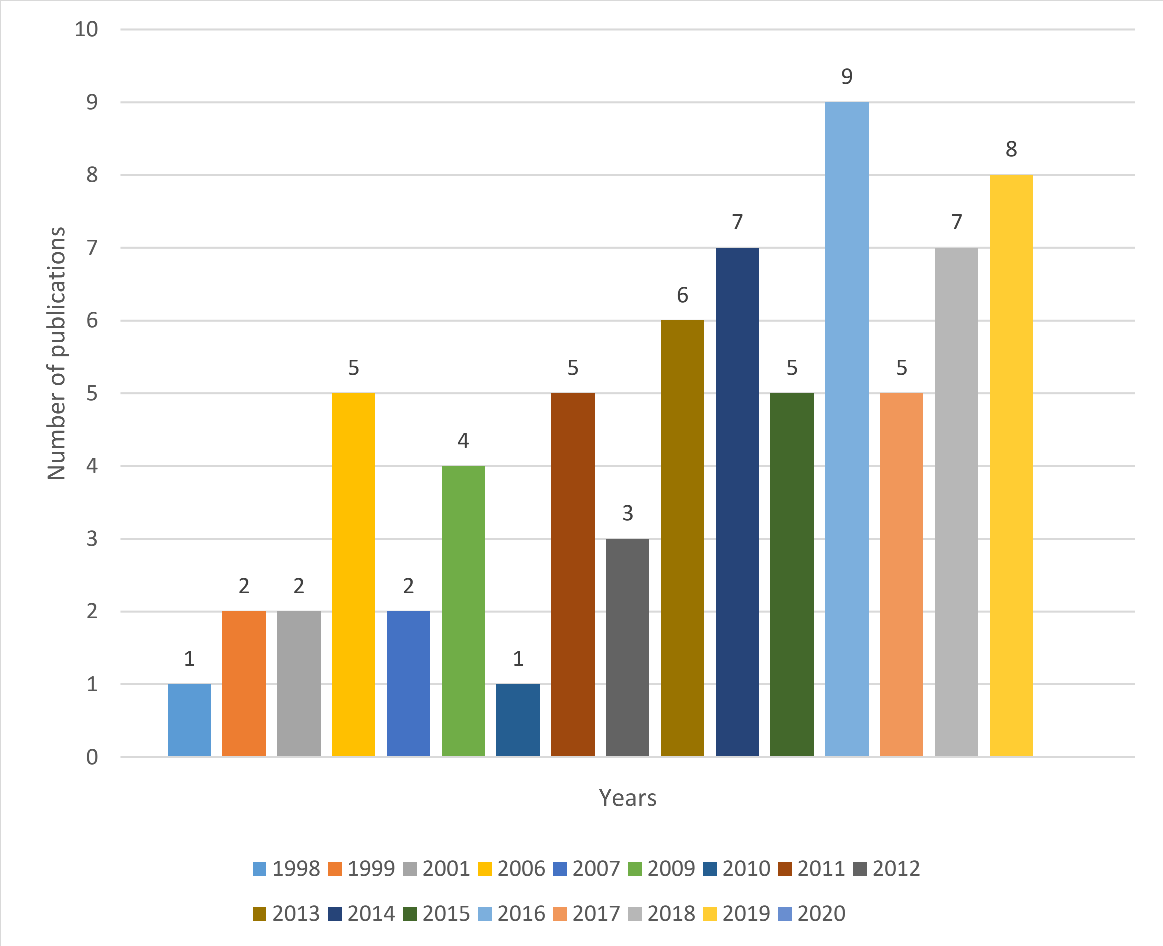

Figure 4.5: Year of publication

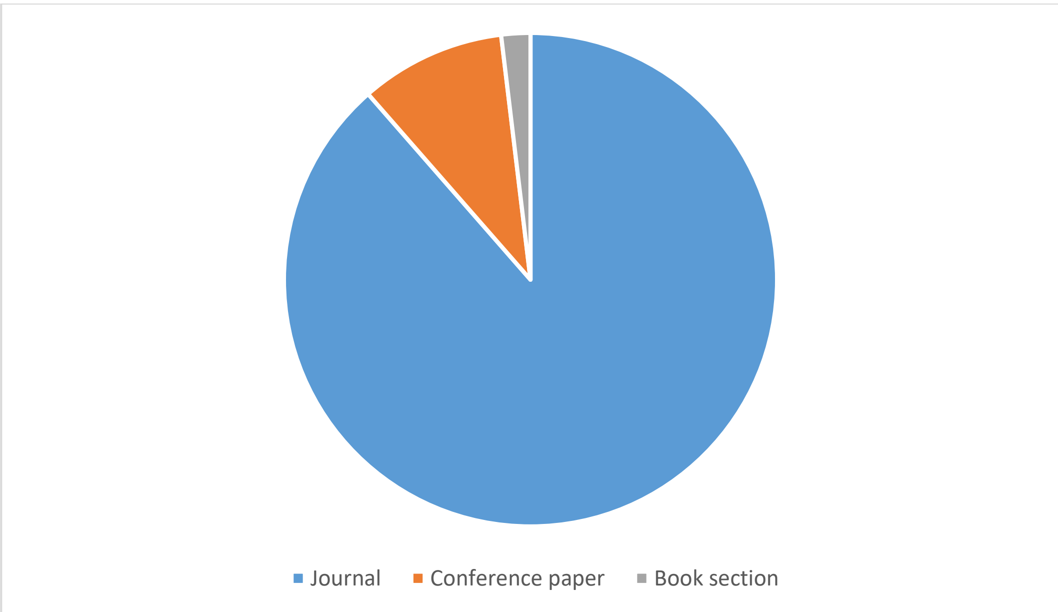

Figure 4.6: Type of publication

Systematic Literature Review (SLR) was conducted to identify maintenance strategy concepts. These concepts were identified from different publications. The aim of unearthing these concepts is to be able to identify all the work needed in implementing a maintenance strategy.

4.7 Conceptual Framework Analysis

According to this research, a research design is a general step-by-step plan that provides a detailed guideline to answering the research question. Important elements of the research design should include research strategies and methods related to data collection and analysis (Dudovskiy, 2018).

In this study, the researcher combines qualitative data from literature and semi-structured interviews to construct a maintenance strategy framework.

The research design in this study is exploratory as it explores different maintenance strategies in the rail environment. The exploratory mixed methods design is used when a researcher first needs to explore a phenomenon using qualitative data before attempting to measure or test it quantitatively (Vos, Strydom and Delport, 2012). The illustration of this exploratory research design is shown in Figure 4.7.

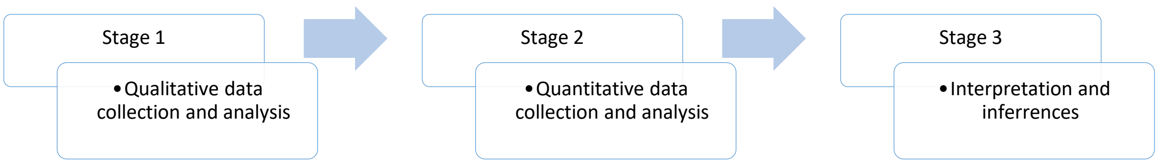

Figure 4.7: Exploratory mixed-method research design (adapted from Strydom et. al. (2012))

4.8 Evaluation Process

Firstly, validation through the Subject Matter Expert (SME) opinion to ascertain the credibility and completeness of the maintenance strategy framework. This stage was conducted with subject matter experts who were selected using purposive sampling. These participants have knowledge and experience of rail maintenance.

4.9 Chapter Summary

The chapter provided an overview of the research methodology. A research design canvas was discussed, which is the guide to the development of the maintenance strategy implementation framework. It outlines the research problem, the purpose of the research, the literature review approach, and the developmental stages of the conceptual maintenance strategy framework. The research onion was adopted for reference on the choice of research philosophy, research strategies, research approaches and the choice of methods. Finally, the research evaluation methodology was outlined.

Chapter 5

CASE STUDY

5.1 INTRODUCTION

The study was done to improve the availability of rolling stock. It is therefore important to analyse one of the rolling stock maintenance depots in order to establish the present state of affairs. It also helps to identify where improvements need to be done. The organisation chosen for this purpose is the Rolling Stock division of PRASA, Salt River depot. A brief background of PRASA is given before providing an overview of the maintenance conducted in the Rolling Stock division of the Salt River depot.

Passenger Rail Agency of South Africa (PRASA) carries out its maintenance of trains in a manner that aims at ensuring safety, availability and reliability. The maintenance that is done at PRASA's Salt River Depot in the Western Cape, South Africa will be described. It is also important to note that this is a region that has the most train commuters in the country, with 14.5 million passenger trips per year. This contributes to about 46% of PRASA's annual income. The region needs 88 trains and but has only 56 at the moment. The region has four corridors that are used for providing services to the citizens.

5.2 BACKGROUND OF PRASA

PRASA, as stated in the PRASA Corporate Plan 2019/21, has the mandate of transporting the public and currently it services urban passengers in four main metropolitan areas in South Africa, namely, KwaZulu-Natal, Gauteng, Eastern Cape and Western Cape. The organisation has more than 270 train sets running over 2228km of the track. It is estimated that PRASA transports 1.7million paying passengers per weekday across South Africa. Most of the train sets currently in operation are ageing, with some having been in operation since 1958. According to PRASA, the first passenger coach arrived in South Africa in 1860, signalling the start of passenger rail transport in the country. The first electric train was called the 2M and was commissioned in 1937 in Johannesburg. Since then, trains have been constantly upgraded and every upgrade was given the next numerical number, for instance 3M, then 4M. Today, the fleet of 270 train sets consist predominantly of the 5M type (as shown in Figure 5.1, commissioned from 1959) as well the 8M, 10M2 and 10M3 types. The missing numbers (6M, 7M and 9M) were prototype trains and are not in use any more. Trains are maintained by

Metrorail on a fortnightly basis while upgrades of trains are done every seven years by private companies (Conradie *et al.*, 2015)

5.3 TRAIN SET CONFIGURATION

According to PRASA, a Motor Coach (MC) (Figure 5.1) is a powered rail vehicle that can transport passengers and pull unpowered Passenger Trailers (PTs). A typical PRASA train set consists of nine PTs and three MCs (one in the middle and one at each end). The contribution of PTs towards the availability of a train set is insignificant compared to the contribution of the MCs. Therefore, for this study, the train set is represented only by the three MCs.

Figure 5.1: Typical 5M Series MC (adapted from Conradie et al. (2015))

Three MCs are required for nine PTs to provide both enough tractive effort as well as system redundancy in the train set. Each MC is identical and the three MCs on a train set are interconnected, whereby certain systems are connected in parallel creating spare capacity (called redundancy). The compressed air system is one such system where the compressors on the three MCs are connected to the same piping system and air tanks, thereby compensating for the pressure drop over the length of the train set and allowing the pressure to build up faster. If one compressor fails, the train set will still be able to complete the mission normally and the compressor can be replaced at the next maintenance interval. If more than one compressor fails, then the train set will not be able to function normally and Breakdown Maintenance is required. The same applies for the vacuum system and 110V power supply system, where a minimum of two out of the three vacuum pumps (also called vacuum exhausters) and a minimum two out of the three supply sets must be functional for the train set to be operational

5.4 MAINTENANCE STRATEGY

PRASA maintains its rolling stock fleet at planned intervals unless there is a breakdown. During the late 1990s, a two-week maintenance interval was adopted by PRASA based on the average distance travelled per train set (Conradie *et al.*, 2015). This two-week interval is still in use today and has not been adapted or changed according to the operational requirements. A train set is, therefore, scheduled for maintenance every two weeks, and the focus and intensity of maintenance will differ during each maintenance intervention. The question is whether the two-week maintenance cycle results in over-maintaining of the train sets thereby wasting valuable resources.

In Metrorail, there are three types of scheduled maintenance interventions (referred to as 'sheds'). A typical eight-week maintenance cycle of any train set is summarised in Table 5.1

Table 5.1: Three types of maintenance activities, spread over an eight-week cycle at PRASA

Week Number	Shed Name	Description
2	A-shed	Passenger Safety and Comfort
4	B-shed	Intermediate shed
6	A-shed	Passenger Safety and Comfort
8	C-shed	Full-shed

The Railway Safety Regulator (RSR), which is the custodian of railway safety in South Africa, requires that passenger and safety inspections are done regularly on each train set, which is two weeks in the case of Metrorail. During the A-Shed, the main focus is the safety and comfort of the passengers, focusing on the functionality of components such as the braking system, wipers, doors and horn. Most of the maintenance activities do not add value to the availability of the train set, hence the name safety and comfort.

During a B- and C-Shed, the maintenance of each component is based on its condition. In these sheds, components are classified in terms of condition. A condition of five indicates the need for a new component; a condition of two means that the component must be replaced at the next maintenance intervention; and a condition of one means that the train set must be removed from service and the component replaced immediately. B-shed and C-shed are applied to components such as traction motors, compressors, 110V supply sets, exhausters, static inverters, pantographs and wheels.

The condition of these components are categorised and captured on checklists and on the Facility Maintenance Management System (FMMS), which is then used to plan interventions based on the conditions equal to two. FMMS is a computerised system which consists of a set of comprehensive management tools developed specifically for maintenance departments. Unfortunately, the criteria used for the classification of these components are not clear and are not sufficiently conclusive to make a confident classification, which leads to questioning the effectiveness of the maintenance intervention decisions.

5.5 Time Spent On Maintenance

The time spent on maintenance was determined using data from 2016 to 2019. The data detailed the job number, sequence number, facility code, job title, facility type, ‘date act’ start, ‘elapsed hours act’ and job reference.

Of importance in this study is the job title, date act start and elapsed hours. The job title indicated the components that were being maintained. This helped in establishing components that are prone to failure and which result in much downtime. Date act start indicated when the maintenance was conducted. Elapsed hours indicated the amount of time spent on maintenance. Date act start and elapsed hours act helped to analyse data as to how much time was spent on maintenance in a given day, week, month, quarter or year, thus enabling downtime of a given period to be established.

Analysis of the data found the following components shown in Figures 5.2 to 5.7 inclusive, to be leading in downtime. Hence, according to PRASA’s component categories they should be part of the mission-critical components.

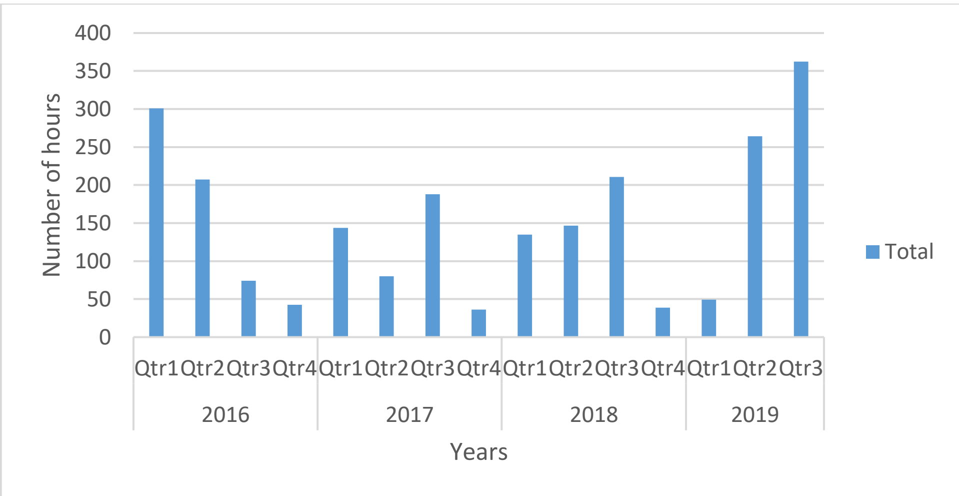

Figure 5.2: Sum of elapsed hours on traction motor maintenance

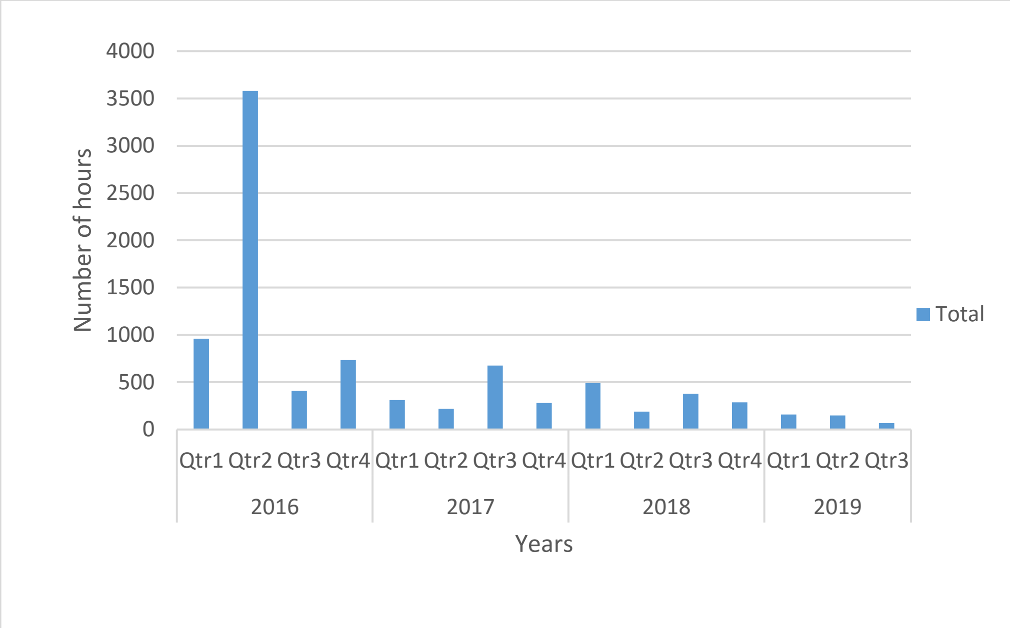

Figure 5.3: Sum of elapsed hours on wheelset maintenance

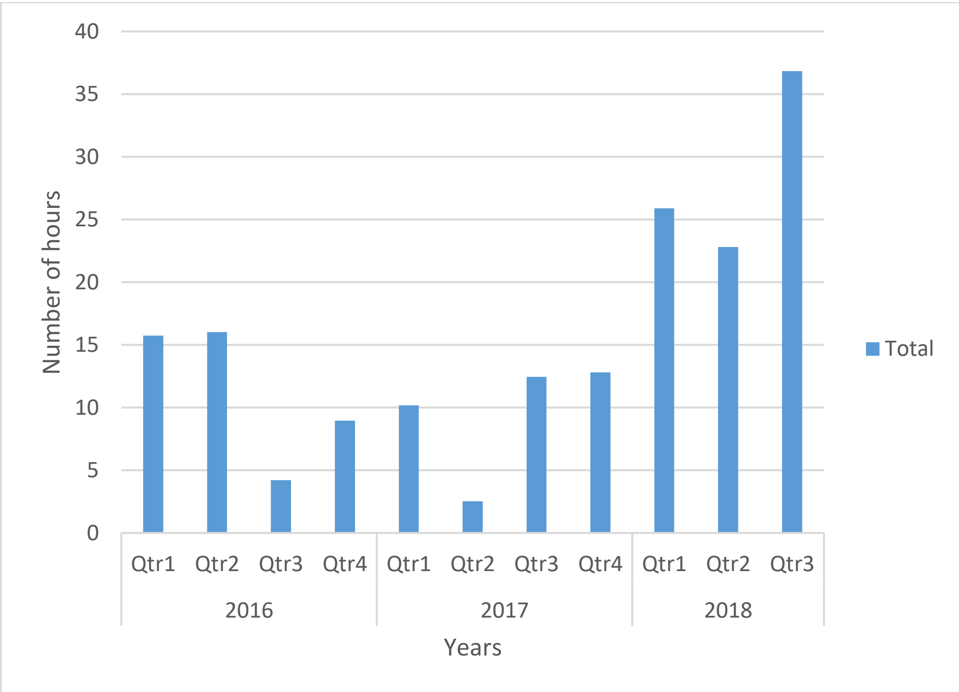

Figure 5.4: Sum of elapsed hours on compressor maintenance

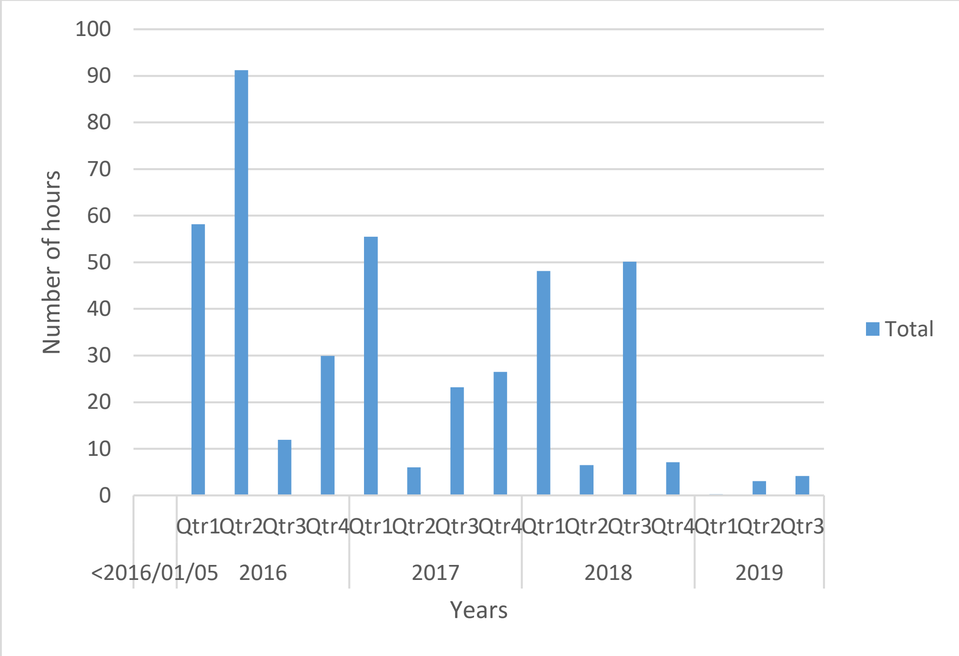

Figure 5.5: Sum of elapsed hours on exhauster maintenance

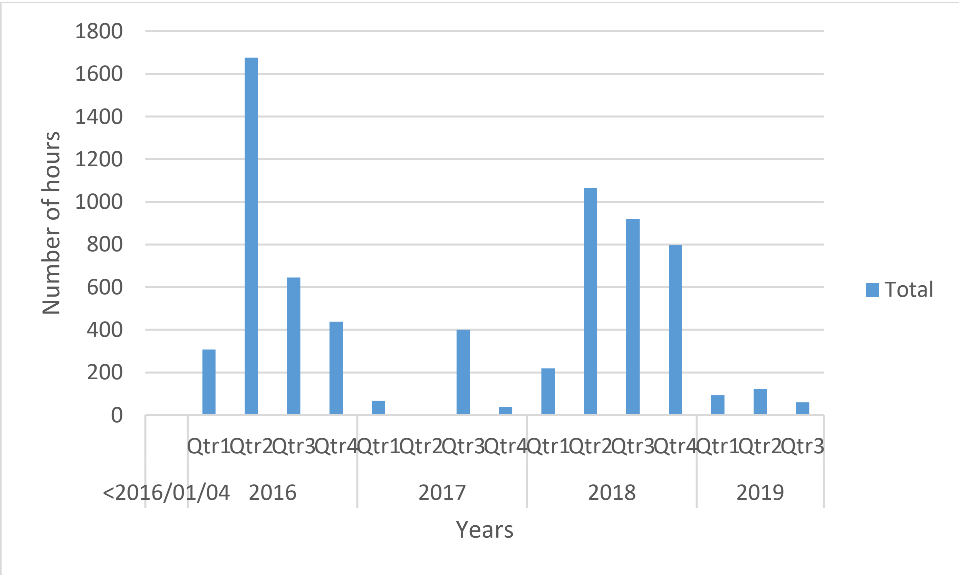

Figure 5.6: Sum of elapsed hours on brakes maintenance

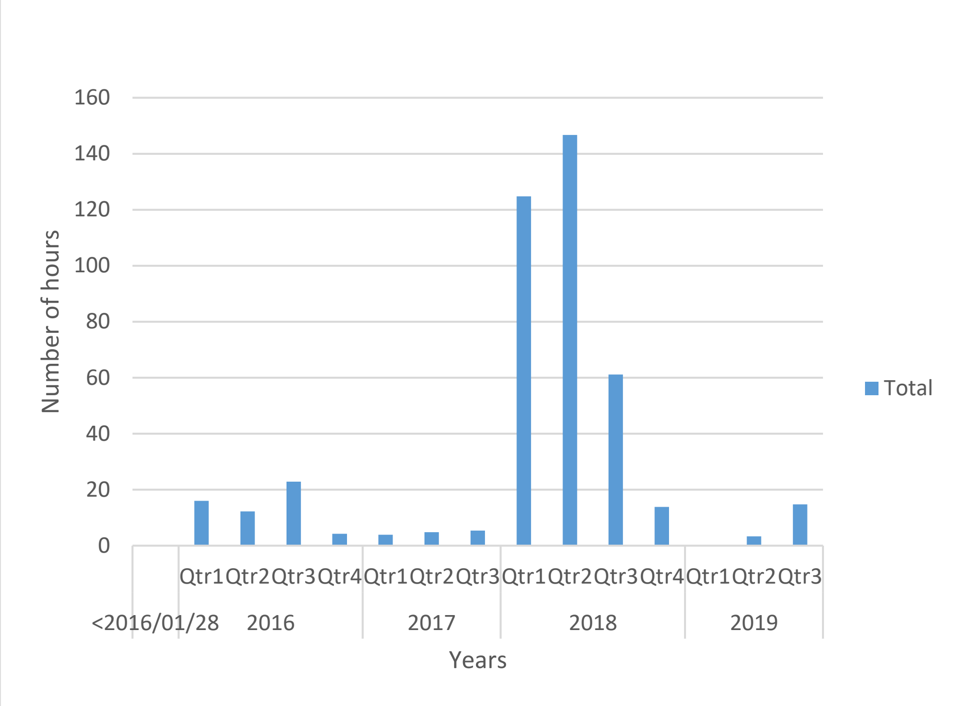

Figure 5.7: Sum of elapsed hours on inverter maintenance

However, the data relating to these components was difficult to analyse. Some entries made were impossible to read. This led to a reduction in the quality of recorded data. For this reason some of the components could not be entered into the study as the data was not readable. For example, there are some entries where zero was entered as the time elapsed during the maintenance, 00:00 hrs being entered as the starting time for maintenance.

It is well established that full shed takes 5 hours, intermediate 3 hours and passenger safety and comfort 2 hours. However, on written historical data, this is not the case, as different values were entered. It is difficult to follow and ascertain the flow of different sheds. It is difficult to see the cycles of the three different sheds. This then raises questions on the accuracy of the entered data. The data also does not give further information as to whether repair or replacement was being done. There is no detail of tasks being carried out save to specify that it was maintenance.

5.6 PROPOSED MAINTENANCE STRATEGY FOR PRASA

As discussed in section 2.5, the selection of a maintenance strategy for an organisation requires several factors to be considered. These factors include tools, type of components, availability of skilled personnel, spare parts, applicability, safety, environmental problems, maintenance costs, mean time between failures, mean time to repair, managements’ view, machine importance to the process and failure frequency.

In selecting a maintenance strategy for PRASA, factors found in the literature which apply to PRASA have been taken into consideration. Factors from the organisation which influence the choice of a maintenance strategy have been considered as well.

A survey conducted by Matsapola (2018), revealed that a condition-based maintenance strategy helps in improving reliability, availability and maintainability of rolling stock vehicles. Research suggests that condition-based maintenance has immeasurable economic benefits. These include the possibility of companies saving up to 20% through the decreased need to keep a stock of spare parts, maintenance costs, decreased downtime, improved product quality, increased reliability and availability of assets (Marcus, 2002).

Organisations implementing a condition-based maintenance strategy can make huge economic savings. A significant amount of money could be saved by implementing this maintenance strategy to address issues affecting performance and availability in a rolling stock maintenance environment (Schlake, 2010). Figure 5.8 shows the estimated annual cost saving due to the implementation of condition-based maintenance.

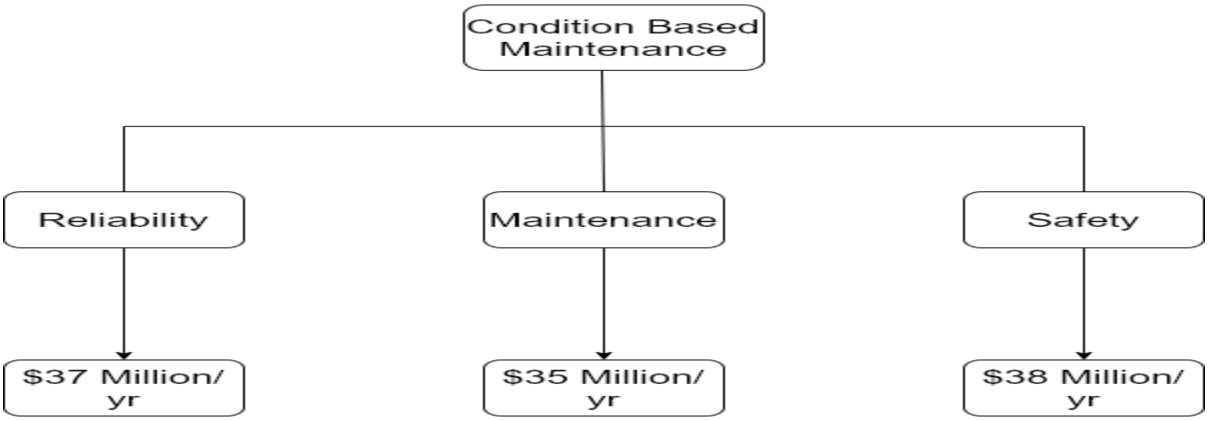

Figure 5.8 Estimated savings due to adoption of CBM (adapted from Schlake (2010))

Proper implementation of condition-based maintenance on rolling stock has a huge impact on rail transportation efficiency. Innovative and effective implementation on rolling stock vehicles could significantly minimise in-service delays, fatal incidents and operational waste (Schlake, Barkan and Edwards, 2011).

Condition-based maintenance seems to be the ideal maintenance strategy in the maintenance of rolling stock. This is further validated by the fact that Transnet, which operates rolling stock, adopted this strategy. Transnet decided to move from preventive maintenance to condition-based maintenance to improve the reliability and availability of rolling stock. The decision was also taken to meet the requirements of Transnet Freight Rail’s (TFR) market demand strategy. The market demand required the optimum operation of their rolling stock fleet. Since PRASA is exposed to the same conditions as Transnet rolling vehicles and shares railway lines, makes it somewhat feasible to adopt a maintenance strategy which seems to be working for Transnet (Solomon, J, Rail, 2012).

According to Asekun and Fourie (2015), many rolling stock organisations globally had adopted either run-to-failure or preventive maintenance strategies. These maintenance strategies were found to be unreliable and ineffective. They led to poor maintenance work, endless failures and additional unnecessary maintenance activities. In the end, most of these railway organisations had to reconsider and ended up adopting condition-based maintenance.

Correct implementation of condition-based maintenance has more merits over other maintenance strategies (Nappi, 2014). Condition-based maintenance is an approach that could unequivocally attain efficiency in a rolling stock vehicle maintenance environment. Condition-based maintenance offers an opportunity for improving rolling stock availability at PRASA

That is not to say condition-based maintenance has no limitations. At times, condition monitoring systems provide false signals. This may lead to an increase in the budget instead of lowering it. Data collection for the monitored components may not be as accurate as it should be. The management of maintenance planning for CBM is complicated and requires a computerised system that would assist with spare parts management, maintenance scheduling and work order management.

The implementation of CBM systems for rolling stock vehicles requires accurate planning. Before the actual development and implementation of the monitoring process, the 'what' and the 'how' should first be defined and well understood by all stakeholders involved (Matsapola, 2018).

PRASA adopted condition-based maintenance in 2009 and is still practising this maintenance strategy to date. PRASA saw the need to review their maintenance strategy after they realised that the PM approach was ineffective, with a lot of wasteful activities related to over-maintenance. However, condition monitoring is conducted visually (Conradie *et al.*, 2015).

From engagements with PRASA management, it was established that there is no maintenance framework for the organisation. This leads to uncertainty about the maintenance strategy being implemented. It is therefore important to develop a maintenance strategy implementation framework. The framework should be in line with the preferred maintenance strategy by PRASA. Also, the framework should utilise a strategy that will ensure the improvement of rolling stock availability.

5.7 CHAPTER SUMMARY

In analysing the Rolling Stock division, Salt River depot and having engagements with PRASA employees, their maintenance doesn 't seem to follow a clear framework. Identifying the maintenance strategy being implemented at PRASA through maintenance records was impossible. Therefore, the organisation, together with the PRASA chair (research group at Stellenbosch University), is currently involved in a project of identifying and evaluating/identifying the maintenance strategy being employed. It is important to note that, if the maintenance strategy is being evaluated by management, it means it is not working properly, hence the need to evaluate it. It therefore means that the decision taken in 2009 by PRASA to adopt condition-based maintenance is not being followed.

At the same time, another project is being done to evaluate the quality of maintenance being rendered. This comes after PRASA lost their ISO9001 licence due to some problems they faced as an organisation. It is therefore important to ensure that a high quality of maintenance is rendered by any strategy that aims to improve the availability of rolling stock.

As discussed in section 5.4, the maintenance strategy presented is condition-based maintenance. However, on closer consideration one discovers that it has some loopholes. For example, at what point does one establish that rolling stock needs to undergo maintenance? According to the data provided, one has to wait for scheduled intervals (different sheds) to establish the actions needed. Then the question should be asked, are these intervals correct for establishing condition? Should the sheds being implemented be at the intervals mentioned? Upon asking these pertinent questions one might discover that it could be preventive maintenance that is being implemented. Should maintenance not be prolonged? Should it not be done more frequently? What then sets the maintenance programme, is it the data acquired or based on instinct?

There is a need for better communication in PRASA on the maintenance strategy the organisation should follow. Maintenance personnel should at any stage be able to spell out the maintenance strategy the organisation is following. For proper implementation of a maintenance strategy, an implementation framework should be developed. The organisation can then use the developed implementation framework to implement the maintenance strategy.

Chapter 6

MAINTENANCE STRATEGY IMPLEMENTATION FRAMEWORK FORMULATION

6.1 INTRODUCTION

Chapter 5 reviewed the maintenance practices at the Passenger Rail Agency of South Africa. This chapter presents the proposed maintenance strategy implementation framework. The framework was developed through a literature review and the gaps in the maintenance strategy being implemented at PRASA.

6.2 CONCEPTUAL ASPECTS

Through a Systematic Literature Review (SLR), 61 maintenance strategy concepts were identified. The identified concepts were then used to formulate a maintenance strategy implementation framework.

Table 6.1: Concepts Identified

Concepts	**References**
Repair	(Mitchell *et al.*, 1995; Vagenas, Runciman and R.clément, 1997; Bevilacqua and Braglia, 2000; Laura, 2001; Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Budai, Dekker and Kaymak, 2009; Sainz and Sebastián, 2013; Zilka, 2014; Irajpour *et al.*, 2014; Do *et al.*, 2015; Ben Said *et al.*, 2016; Morant, Larsson-Kråik and Kumar, 2016; Makasheva, 2016; Alaswad and Xiang, 2017; Nazeri and Naderikia, 2017; Patidar, Soni and Soni, 2017; Vilarinho, Lopes and Oliveira, 2017; Sahoo, 2019)
Replace	(Vagenas, Runciman and R.clément, 1997; Laura, 2001; Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Zilka, 2014; Irajpour *et al.*, 2014; Do *et al.*, 2015; Morant, Larsson-Kråik and Kumar, 2016; Alaswad and Xiang, 2017; Vilarinho, Lopes and Oliveira, 2017; Nazeri and

	Naderikia, 2017; Patidar, Soni and Soni, 2017; Selcuk, 2017; Sahoo, 2019)
Inspect	(Vagenas, Runciman and R.clément, 1997; Zilka, 2014; Bengtsson, 2014; Andrés, Cadarso and Marín, 2015; He, Maillart and Prokopyev, 2015; Stenström *et al.*, 2016; Ben Said *et al.*, 2016; Alaswad and Xiang, 2017; Vilarinho, Lopes and Oliveira, 2017; Nazeri and Naderikia, 2017; Patidar, Soni and Soni, 2017; Selcuk, 2017; Söderholm and Nilsen, 2017; Sahoo, 2019)
Coordination	(Mckone, Schroeder and Cua, 2001; Waeyenbergh and Pintelon, 2002; Singh, A. Gupta, *et al.*, 2016b; Duran, Capaldo and Acevedo, 2017; Luan *et al.*, 2017; Patidar, Soni and Soni, 2017)
Availability	(Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Bevilacqua and Braglia, 2000; M. C. Eti, Ogaji and Probert, 2006b; Rezvanizaniani, Barabady and Kumar, 2009; Afefy, 2010; Van de Pieterman *et al.*, 2011; Cane, 2011; Soh, Radzi and Haron, 2012; Sainz and Sebastián, 2013; Kumar *et al.*, 2013a; Alabdulkarim, Ball and Tiwari, 2014b; Cromie *et al.*, 2015; Stenström *et al.*, 2016; Karunakaran, 2016; Selcuk, 2017; Duran, Capaldo and Acevedo, 2017; Li *et al.*, 2017; Sahoo, 2019; Shafiee *et al.*, 2019; Shou *et al.*, 2019)
Quality of service	(Soh, Radzi and Haron, 2012; Kumar *et al.*, 2013a; Lobna, Mounir and Hichem, 2013; Alabdulkarim, Ball and Tiwari, 2014b; Selcuk, 2017; Shou *et al.*, 2019)
Customer safety	(Rezvanizaniani *et al.*, 2009; Cane, 2011; Van de Pieterman *et al.*, 2011; Sainz and Sebastián, 2013; Alabdulkarim, Ball and Tiwari, 2014b; Irajpour *et al.*, 2014; Stenström *et al.*, 2016; Li *et al.*, 2017; Rana and Koroitamana, 2018; Shafiee *et al.*, 2019)
Reliability	(Vagenas, Runciman and R.clément, 1997; Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Bevilacqua and Braglia, 2000; Skarlatos, Karakasis and Trochidis, 2004; Stratman, Liu and Mahadevan, 2007; Rezvanizaniani *et al.*, 2009;

	Afefy, 2010; Pombo *et al.*, 2010; Cane, 2011; Van de Pieterman *et al.*, 2011; Gomes and Yasin, 2011; Soh, Radzi and Haron, 2012; Sainz and Sebastián, 2013; Kumar *et al.*, 2013a; Irajpour *et al.*, 2014; Stenström *et al.*, 2016; Makasheva, 2016; Selcuk, 2017; Li *et al.*, 2017; Rana and Koroitamana, 2018; Shafiee *et al.*, 2019; Shou *et al.*, 2019)
Safety of maintenance personnel	(Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Peng *et al.*, 2011)
Frequency of maintenance	(Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Vagenas, Runciman and R.clément, 1997; Rezvanizaniani *et al.*, 2008; Budai, Dekker and Kaymak, 2009; Vilarinho, Lopes and Oliveira, 2017; Seecharan, Labib and Jardine, 2018)
Determine maintenance actions	(M. C. Eti, Ogaji and Probert, 2006b; Rezvanizaniani *et al.*, 2008; Bazrafshan and Hajjari, 2012; Lobna, Mounir and Hichem, 2013; Irajpour *et al.*, 2014; Shou *et al.*, 2019)
Spare parts management	(Organ *et al.*, 1997; Crespo Marquez and Gupta, 2006; M. C. Eti, Ogaji and Probert, 2006b; Irajpour *et al.*, 2014; Zilka, 2014; Mishra *et al.*, 2015a; Rana and Koroitamana, 2018; Shafiee *et al.*, 2019)
Number of maintenance personnel needed	(Organ *et al.*, 1997; Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Stenström *et al.*, 2016; Rana and Koroitamana, 2018; Shafiee *et al.*, 2019)
Level of technical skill needed	(Mitchell *et al.*, 1995; Jonsson, 1997; Organ *et al.*, 1997; Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Gomes and Yasin, 2011; Do *et al.*, 2015; Stenström *et al.*, 2016; de Jonge, Teunter and Tinga, 2017; Naji *et al.*, 2018; Semma, Mousrij and Gziri, 2018; Shafiee *et al.*, 2019; Turabimana and Nkundineza, 2020)
Tools	(Jonsson, 1997; Organ *et al.*, 1997; M. C. Eti, Ogaji and Probert, 2006b; Cane, 2011; Stenström *et al.*, 2016; Rana and Koroitamana, 2018; Shafiee *et al.*, 2019; Turabimana and Nkundineza, 2020)
Allocation of resources	(Vagenas, Runciman and R.clément, 1997; Organ *et al.*, 1997; M. C. Eti, Ogaji and Probert, 2006b; Gomes and Yasin, 2011;

	Peng *et al.*, 2011; Kumar *et al.*, 2013a; Pogačnik, Tavčar and Duhovnik, 2015; Karunakaran, 2016; Singh, A. K. A. Gupta, *et al.*, 2016; Stenström *et al.*, 2016; Vilarinho, Lopes and Oliveira, 2017; Rana and Koroitamana, 2018)
Maintenance procedure	(Mitchell *et al.*, 1995; Rezvanizaniani *et al.*, 2008; Bazrafshan and Hajjari, 2012; Mishra *et al.*, 2015a; Karunakaran, 2016; Nazeri and Naderikia, 2017)
Time allocation	(Organ *et al.*, 1997; Vagenas, Runciman and R.clément, 1997; Waeyenbergh and Pintelon, 2002; Budai, Dekker and Kaymak, 2009; Soh, Radzi and Haron, 2012; Singh, A. Gupta, *et al.*, 2016a; Stenström *et al.*, 2016; Nazeri and Naderikia, 2017; Selcuk, 2017; Shafiee *et al.*, 2019)
Competency	(Jonsson, 1997; Mckone, Schroeder and Cua, 2001; Cane, 2011; Gomes and Yasin, 2011; Do *et al.*, 2015; Makasheva, 2016; Stenström *et al.*, 2016; Naji *et al.*, 2018)
Flow of information	(Jonsson, 1997; Cane, 2011)
Management commitment	(Jonsson, 1997; Organ *et al.*, 1997; Waeyenbergh and Pintelon, 2002; M. C. Eti, Ogaji and Probert, 2006b; Gomes and Yasin, 2011; Karunakaran, 2016; Singh, A. K. A. Gupta, *et al.*, 2016; Duran, Capaldo and Acevedo, 2017; Naji *et al.*, 2018)
Communication	(Jonsson, 1997; Gondal, Shahbaz and Shahbaz, 2012; Singh, A. Gupta, *et al.*, 2016b)
Procurement of needed resources	(Mitchell *et al.*, 1995; Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Organ *et al.*, 1997; Crespo Marquez and Gupta, 2006; Mishra *et al.*, 2015a; Selcuk, 2017)
Work order	(Waeyenbergh and Pintelon, 2002; Carretero *et al.*, 2003; Crespo Marquez and Gupta, 2006)
Computer maintenance management	(Vagenas, Runciman and R.clément, 1997; Crespo Marquez and Gupta, 2006)
Formation of teams	(Organ *et al.*, 1997; Crespo Marquez and Gupta, 2006; M. C. Eti, Ogaji and Probert, 2006b; Dhillon, 2010)

Continuous technical and interpersonal training of maintenance personnel	(Mitchell *et al.*, 1995; Organ *et al.*, 1997; Mckone, Schroeder and Cua, 2001; Waeyenbergh and Pintelon, 2002; Crespo Marquez and Gupta, 2006; M. C. Eti, Ogaji and Probert, 2006b; Gomes and Yasin, 2011; Sainz and Sebastián, 2013; Bramer, 2016; Singh, A. Gupta, *et al.*, 2016b; Selcuk, 2017; Shafiee *et al.*, 2019; Sahoo, 2019)
Reduction of downtime	(Mitchell *et al.*, 1995; Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Carretero *et al.*, 2003; M. C. Eti, Ogaji and Probert, 2006b; Rezvanizaniani *et al.*, 2008; Afefy, 2010; Zilka, 2014; Pogačnik, Tavčar and Duhovnik, 2015; Karunakaran, 2016; Makasheva, 2016; Caldera, Desha and Dawes, 2017; Seecharan, Labib and Jardine, 2018; Thapa, Saldanha and Prakash, 2018; Sahoo, 2019; Shafiee *et al.*, 2019)
Adjustments	(Soh, Radzi and Haron, 2012; Sainz and Sebastián, 2013; Irajpour *et al.*, 2014; Pogačnik, Tavčar and Duhovnik, 2015; Morant, Larsson-Kråik and Kumar, 2016; Luan *et al.*, 2017; Sahoo, 2019)
Lubrication	(Soh, Radzi and Haron, 2012; Irajpour *et al.*, 2014; Lin, Pulido and Asplund, 2015; Morant, Larsson-Kråik and Kumar, 2016; Stenström *et al.*, 2016; Phogat and Gupta, 2017)
Operating time	(Waeyenbergh and Pintelon, 2002; Garg and Deshmukh, 2006; Bengtsson, 2014; Andrés, Cadarso and Marín, 2015; Phogat and Gupta, 2017)
Age of equipment	(Carretero *et al.*, 2003; Karunakaran, 2016; Phogat and Gupta, 2017; Vilarinho, Lopes and Oliveira, 2017)
Reduction of unexpected failures	(Organ *et al.*, 1997; Soh, Radzi and Haron, 2012; Karunakaran, 2016; Ravi, Mohd Drus and Krishnan, 2019; Sahoo, 2019)
Labour costs	(Soh, Radzi and Haron, 2012; Singh, A. Gupta, *et al.*, 2016b; de Jonge, Teunter and Tinga, 2017)
Inventory cost	(Soh, Radzi and Haron, 2012; Singh, A. Gupta, *et al.*, 2016b; Semma, Mousrij and Gziri, 2018)

Historical data collection and processing	(Waeyenbergh and Pintelon, 2002; Van de Pieterman *et al.*, 2011; Sainz and Sebastián, 2013; Bengtsson, 2014; Alaswad and Xiang, 2017; Vilarinho, Lopes and Oliveira, 2017; Semma, Mousrij and Gziri, 2018)
Tightening	(Soh, Radzi and Haron, 2012; Irajpour *et al.*, 2014)
Cleaning	(Soh, Radzi and Haron, 2012; Irajpour *et al.*, 2014)
Legislation and rules	(Rezvanizaniani *et al.*, 2008; Karunakaran, 2016)
Use of scheduling software	(Sriskandarajah, Jardine and Chan, 1998; Budai, Dekker and Kaymak, 2009; Peng *et al.*, 2011; Zilka, 2014; Vilarinho, Lopes and Oliveira, 2017; Gandhare, Akarte and Patil, 2018)
Allocation of maintenance tasks	(Mitchell *et al.*, 1995; Peng *et al.*, 2011; Bazrafshan and Hajjari, 2012; Soh, Radzi and Haron, 2012)
Monitoring	(Jardine, Lin and Banjevic, 2006; Afefy, 2010; Roger, 2011; Sainz and Sebastián, 2013; Zilka, 2014; Irajpour *et al.*, 2014; Weston *et al.*, 2015; Makasheva, 2016; Alaswad and Xiang, 2017; Vilarinho, Lopes and Oliveira, 2017; Li *et al.*, 2017; Phogat and Gupta, 2017; Semma, Mousrij and Gziri, 2018)
Equipment technical condition	(Picknell and Campbell, 1999; Waeyenbergh and Pintelon, 2002; Bengtsson, 2014; Zilka, 2014; Do *et al.*, 2015; Karunakaran, 2016; Ji *et al.*, 2017; Rana and Koroitamana, 2018)
Level of maintenance	(Andrés, Cadarso and Marín, 2015; Selcuk, 2017)
Stock tracking	(Organ *et al.*, 1997; Waeyenbergh and Pintelon, 2002; Bertolini and Bevilacqua, 2006)
Recording	(Picknell and Campbell, 1999; M. C. Eti, Ogaji and Probert, 2006b; Morant, Larsson-Kråik and Kumar, 2016; Stenström *et al.*, 2016; Alaswad and Xiang, 2017)
Document control	(Waeyenbergh and Pintelon, 2002)
Failure mode	(Picknell and Campbell, 1999; Bevilacqua and Braglia, 2000; Waeyenbergh and Pintelon, 2002; Rezvanizaniani *et al.*, 2008; Vilarinho, Lopes and Oliveira, 2017; Shafiee *et al.*, 2019)

Grouping components	(Waeyenbergh and Pintelon, 2002; Ji *et al.*, 2017; Semma, Mousrij and Gziri, 2018)
Failure rate	(Mitchell *et al.*, 1995; Vagenas, Runciman and R.clément, 1997; Picknell and Campbell, 1999; Waeyenbergh and Pintelon, 2002; Cane, 2011; Bazrafshan and Hajjari, 2012; Sainz and Sebastián, 2013; Irajpour *et al.*, 2014; Ji *et al.*, 2017; Thapa, Saldanha and Prakash, 2018; Seecharan, Labib and Jardine, 2018; Ravi, Mohd Drus and Krishnan, 2019; Shafiee *et al.*, 2019)
Protection of environment	(Gomes and Yasin, 2011; Kumar *et al.*, 2013b; Sainz and Sebastián, 2013; Selcuk, 2017; Sahoo, 2019)
Benchmarking	(Singh, A. Gupta, *et al.*, 2016b)
Failure effect	(Rezvanizaniani *et al.*, 2008; Sainz and Sebastián, 2013; Irajpour *et al.*, 2014)
Overhauling	(Makasheva, 2016; Sahoo, 2019)
Servicing	(Sahoo, 2019)
Testing	(Sainz and Sebastián, 2013; Sahoo, 2019)
Measuring	(Sainz and Sebastián, 2013; Sahoo, 2019; Turabimana and Nkundineza, 2020)
Contracting	(Espling, 2007; Rana and Koroitamana, 2018)
Reporting	(Espling, 2007; Gomes and Yasin, 2011)
Scheduling	(Horner, R.M.W.; EL-Haram, M A; Munns, 1997; Sriskandarajah, Jardine and Chan, 1998; Maróti and Kroon, 2007; Rezvanizaniani *et al.*, 2008; Budai, Dekker and Kaymak, 2009; Peng *et al.*, 2011; Elsayed EA, 2012; Andrés, Cadarso and Marín, 2015; Lin, Pulido and Asplund, 2015; de Jonge, Teunter and Tinga, 2017; Thapa, Saldanha and Prakash, 2018; Rana and Koroitamana, 2018)

6.2.1 Categorisation of concepts

The identified concepts were then grouped into 8 categories as shown in Table 6.2

Table 6.2: Concept categories

Objectives Availability, Reliability, Reduction of unexpected failures, Reduction of downtime, Customer safety, Quality service, Protection of environment	**Personnel** Level of technical skill needed, Number of maintenance personnel needed, Competency, Continuous technical and interpersonal training of maintenance personnel, Communication Management commitment
Data acquisition and analysis Reporting, Failure effect, Benchmarking, Failure rate, Failure mode, Stock tracking, Equipment technical condition, Monitoring, Legislation and rules, Historical data collection and processing, work order, Age of equipment, Operating time, Work order, Flow of information, CMMS	**Materials requirements** Spare parts management, Inventory cost, Labour cost, Tools
Planning Grouping of components, Level of maintenance needed, Procurement, Time allocation, Allocation of resources, Frequency of maintenance, Allocation of maintenance tasks, Coordination, Use of scheduling software, Formation of maintenance teams, Determining maintenance actions, Contracting	**Execution** Measuring, Testing, Servicing, Overhauling, Inspecting, Replacing, Repairing, Cleaning, Tightening, Lubricating, Adjustment, Coordination, Recording
Maintenance programme Maintenance procedure Benchmarking	**Scheduling** Scheduling

6.3 FRAMEWORK DEVELOPMENT

The identified concepts and subsequently their categories were synchronised to establish a comprehensive maintenance strategy framework. The framework development provides steps undertaken to come up with a maintenance strategy implementation framework for the rail environment. The framework gives an outline of how a maintenance strategy can be implemented by an organisation.

6.3.1 Towards a maintenance strategy framework

As shown in section 6.2.1, concepts were grouped into different categories. Figure 6.1: Interaction of categories shows how these different categories interact with each other. The interaction gives a full picture of the maintenance process in the rail environment.

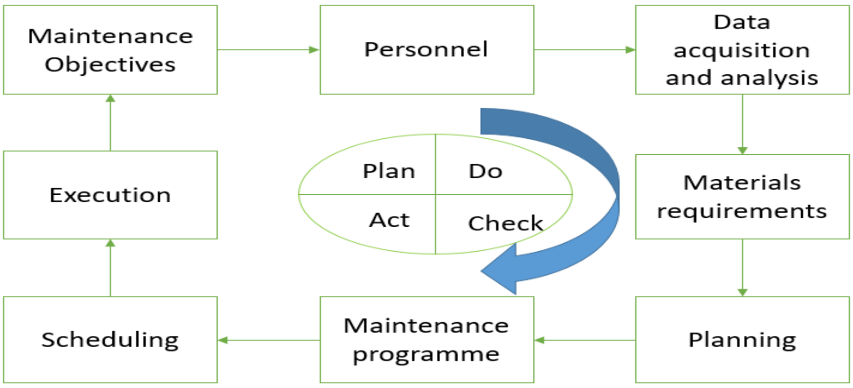

Figure 6.1: Interaction of categories

The maintenance process will start with the organisation spelling out their maintenance objectives (Espling, 2007; Johansson and Rudberg, 2010; Velmurugan, R.S, Dhingra, 2015; Asset and Plan, 2020). This helps the organisation to focus on what is important to them and ensure that it is in line with their business objectives. In the rail environment, reliability, availability and care for the environment should be of concern. These maintenance objectives help to identify the kind of personnel needed in the maintenance department hence as depicted by Figure 6.1, it is followed by personnel.

Personnel identified should have the required technical skills to enable the organisation to meet the maintenance objectives. Based on the need to strive for excellence all the time, personnel must be continuously trained.

When the personnel assigned to perform different duties have been identified, the organisation's equipment is assessed through inspection, historical data or any other method to determine the necessary tasks that need to be performed. The full determination of what needs to be done helps in identifying the kind of material (spare parts and tools) that will be needed and in what quantity.

Material requirements are determined by the condition of the equipment. These are tools and spare parts needed to restore the equipment to operation. Material quantity is easy to establish as on data acquisition and analysis, inventory levels would have been identified; therefore the difference between what is needed and what is available would need to be purchased.

Personnel, data acquisition and analysis and materials requirements can be grouped into resource requirements. Hence, when resource requirements have been established, planning for maintenance needs to take place. At this stage, maintenance teams are formed based on the personnel available, tasks to be performed and the objectives of carrying out those tasks (Espling, 2007; Johansson and Rudberg, 2010).

Maintenance programmes specify the level of maintenance that needs to be undertaken and when it should be done. This phase also specifies the maintenance procedure. This helps to establish a standardised way of doing things. Standardisation improves maintenance task control and helps in improving the quality of maintenance (Espling, 2007; Zhang *et al.*, 2017).

When the maintenance programme has been established, scheduling has to be done. Scheduling aims to bring together everything that is needed, such as resources (spare parts, tools, personnel and equipment) to the right place (Zhang *et al.*, 2017).

Upon bringing all requirements to the right places, the execution of maintenance tasks has to be undertaken (Espling, 2007; Johansson and Rudberg, 2010; Zhang *et al.*, 2017). These include cleaning, lubricating, repairing or replacement, depending on the level of maintenance established through the maintenance program.

The maintenance process is evolutionary, it follows the Plan-Do-Check-Act (PDCA) principle. It is the process of continuous improvement (Espling, 2007; Johansson and Rudberg, 2010; Chaïb *et al.*, 2014). The PDCA principle aligns with the ISO55000 Asset Management Standard (Asset and Plan, 2020).

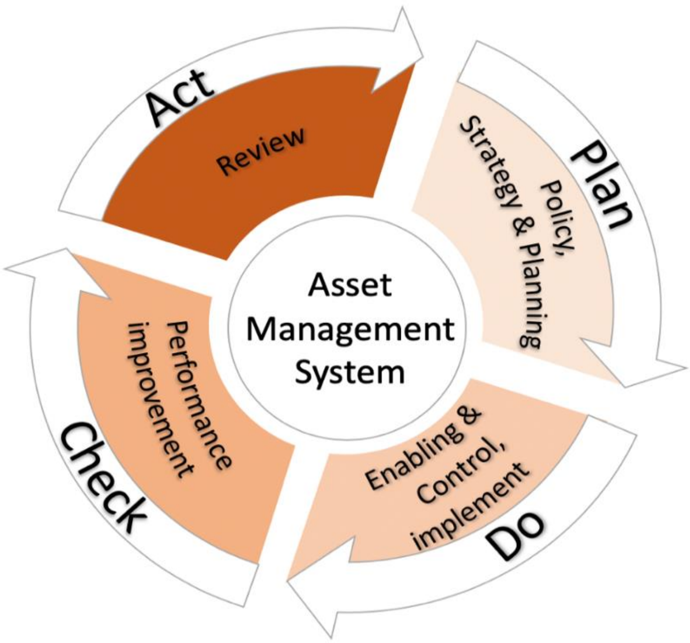

Figure 6.2: Plan-Do-Act-Check cycle

6.3.2 Development of a maintenance strategy framework

The developed framework synchronised all the concepts identified in section 6.2. The framework starts with the business objectives which are translated into maintenance objectives. It helps to bridge the gap between business strategy and maintenance strategy. This leads to an effective formulation of a maintenance strategy (Kelly, 2006; Pintelon and Parodi-herz, 2008; Silonen, 2011).

The maintenance objectives lead to operation and maintenance requirements. This stage consists of tactical and operational planning (Pintelon LM, 1992). Maintenance strategy elements such as materials requirements, personnel, and data acquisition and analysis are then included (M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006).

When the operation and maintenance requirements have been established, a specific maintenance programme is formulated. It consists of planning and a maintenance programme. Maintenance tasks that need to be performed are established. Scheduling of tasks and maintenance resources are also done (Pintelon LM, 1992; Kelly, 2006; Muchiri *et al.*, 2011).

This is followed by maintenance execution. On maintenance execution, the identified maintenance tasks used in coming up with a specific maintenance programme will be performed (M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006; Muchiri *et al.*, 2011). Analysis of the repaired equipment has to then be done. The results of the analysis are fed back to the programme as an input, hence the need for a feedback loop (Pintelon LM, 1992; M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006; Espling, 2007).

Maintenance strategy should be optimised to improve the quality of maintenance. With any specific maintenance programme, maintenance execution should be under continuous improvement (Pintelon LM, 1992; M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006).

For the organisation to successfully evaluate its progress, it has to put a maintenance measurement system in place. This could be done through benchmarking. This helps in continuous improvement (M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006; Muchiri *et al.*, 2011).

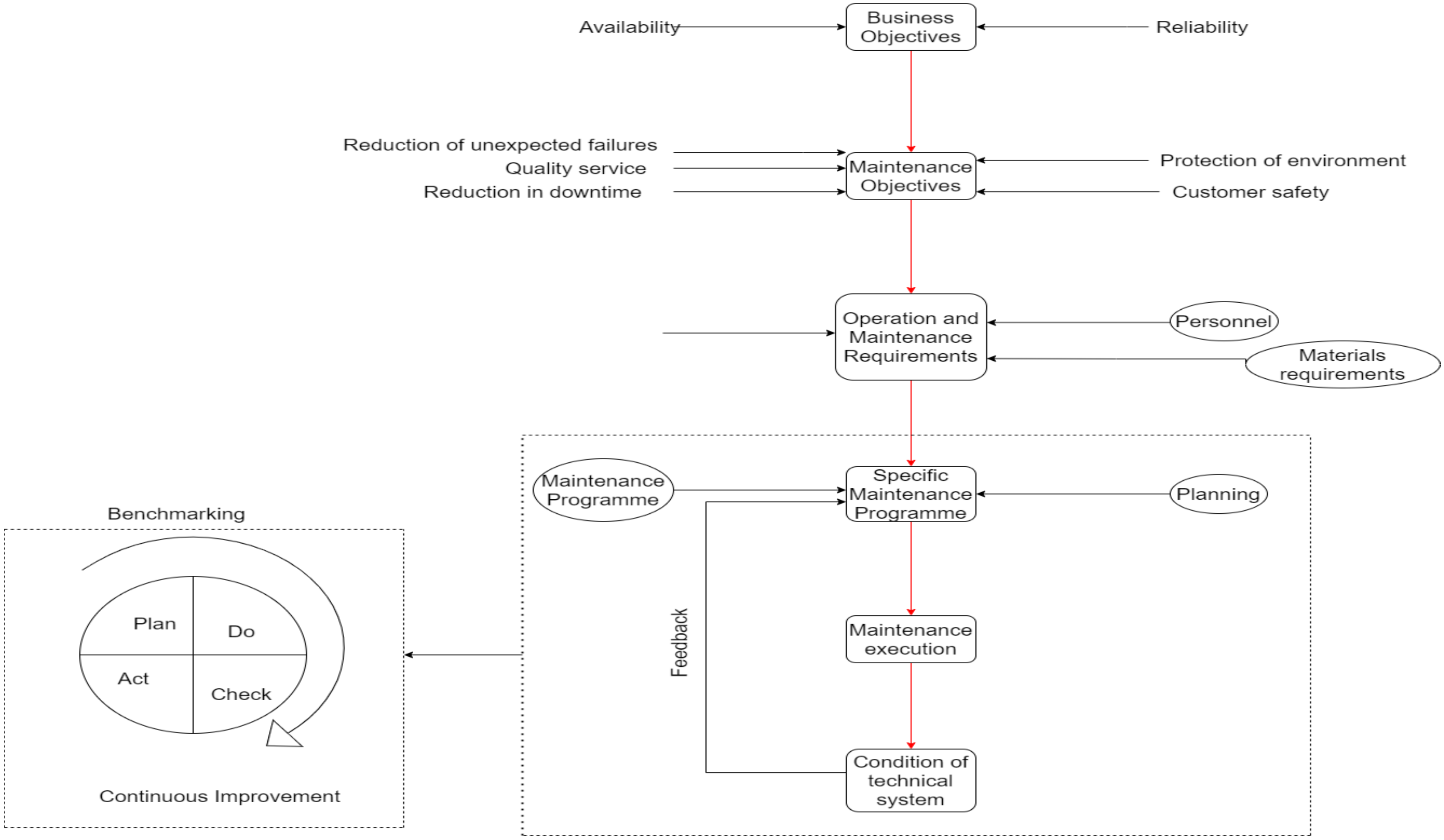

Figure 6.3: Developed maintenance strategy framework

The developed framework starts with business objectives. This helps to identify the direction which the organisation wants to take. It is also used to identify the prioritised objectives of the organisation. Identifying these helps the maintenance department to be aware of and formulate their role in the organisation (Kelly, 2006; Pintelon and Parodi-herz, 2008; Silonen, 2011). PRASA's main business objectives are availability and reliability. The proposed framework mainly targets improving the availability of rolling stock.

The business objectives set out the direction for maintenance objectives. PRASA (with reliability and availability being the main business objectives) should then spell out maintenance objectives. These maintenance objectives are to make meeting the business objectives a reality (Muchiri *et al.*, 2011). Therefore the maintenance objectives are derived from the business objectives. For PRASA to ensure high rolling stock availability, maintenance objectives should include reduction of unexpected failures, improvement in the quality of service, reduction in downtime, protection of the environment and improvement in customer safety.

After establishing maintenance objectives, ways on how these objectives will be met should be established. Some of the ways in which PRASA should be able to establish these are by data collection of maintenance activities and analysing them. Through data acquisition and analysis, it is possible to identify the technical condition of the equipment, previous maintenance that was carried out and spare parts needed (Eti, Ogaji and Probert, 2006). These then help to establish what needs to be done to avoid failure and the kind of personnel required to carry out the different maintenance tasks.

The maintenance plan is developed based on the findings from the data acquisition and analysis stage. The maintenance plan determines when the maintenance is going to be carried, how it will be carried out and the personnel involved. It is important that all components that have identified signs of failure be maintained.

The next step is then to execute maintenance work. This consists of cleaning, lubricating, measuring, testing, replacing and repairing among other tasks. These should be carried out by trained, competent personnel to keep the quality of maintenance high (Espling, 2007).

The whole process must be then be subjected to some level of quality improvement. In Figure 6.2, it is presented as the Plan-Do-Check-Act cycle.

Plan – It is done to establish measures. It is the stage where success factors of maintenance are identified. At PRASA these are the business objectives. Measurements that will assess performance should be identified. Targets which actual performance must meet should be set. These include downtime and failure rate.

Do – Execute activities and record data that helps to assess performance.

Check – Compare actual performance with target previously establish and understand the reasons for variances.

Act – Take action to improve performance.

6.4 CHAPTER SUMMARY

Based on an extensive review of the maintenance literature from different environments including the global railway sector, a framework for a maintenance strategy has been developed. In conducting the literature review, maintenance tasks/activities, objectives, criteria for selecting maintenance actions and when they should be performed were identified for the formulation of a maintenance strategy framework.

The framework regards business objectives, regulations, health, safety and environment demands and interaction between different maintenance tasks. The maintenance strategy framework includes possible phases of activities, such as objectives, personnel, scheduling, data acquisition and analysis, materials requirements, maintenance programme and maintenance plan, and execution of maintenance tasks and the continuous improvement of a maintenance process are given.

The next step of the research was to validate the framework. This was done by conducting interviews with experts in the field such as rail maintenance practitioners.

Chapter 7

VALIDATION OF THE MAINTENANCE STRATEGY IMPLEMENTATION FRAMEWORK

7.1 INTRODUCTION

The study used five phases to develop a comprehensive maintenance strategy framework that can be used in a rail environment. The framework regards business objectives, regulations, health, safety and environment demands and interaction between different maintenance strategy factors. In establishing such a framework, it follows that the principles of validity and reliability are fundamental in ensuring that the research product is valuable and useful (Jabareen, 2009).

This chapter aims to verify and validate the maintenance strategy implementation framework consistent with objective 6 in section 1.5 of this study, which is to verify and validate the framework using validation interviews with subject matter experts (SMEs). Validation interviews and iterative improvement of the framework were conducted based on feedback from SMEs.

Reliability in this context is the extent to which the results of a study are consistent over time. It also measures the accuracy of the representation of the total population under study (Bryman *et al.*, 2014). Reliability of the findings is evaluated by verification of the study which entails the assessment of whether the solution was developed correctly. Verification refers to mechanisms that are employed in the framework development process to incrementally contribute to reliability and validity, to demonstrate the thoroughness of the study. Verification will aid in determining whether the solution is of high quality and complete, though it will not necessarily ensure that the solution is useful in addressing the original problem.

Validity addresses the aforementioned gap by demonstrating the integrity of the solutions from the study and ensuring that the research output truly addresses the investigated concept, providing the appropriate answers. The focus of validation is on the link between the purpose and the context of the research study and conclusions, thus assessing whether the developed solution addresses the defined problem. Kothari (2004) defines two forms of validity, namely external validity, which focuses on the extent to which a solution can be generalised from the view of its relevance to a larger population, and internal validation, which comprises the following three distinct concepts:

1. Criterion validity—which evaluates the extent to which applicable features of the solution can be precisely forecasted by the theoretical concept.
2. Face validity (also referred to as content validity)—which assesses the extent to which a solution provides adequate coverage of the topic under study.
3. Construct validity—which tests whether the solution addresses what it claims to solve and that the solution does not assess irrelevant attributes.

Validation is commonly achieved via three main approaches, namely:

1. Interviews with subject matter experts (SMEs);
2. Implementation;
3. Case study application (Mouton, 2001).

Each of these approaches has its advantages and disadvantages. Validation for this study was done through interviews with the subject matter experts. Therefore, the focus from here on will be on these interviews with the SMEs. These are interviews where the interviewer gathers knowledge from the interviewee to disprove or validate claims made by the researcher. These interviews can be structured, semi-structured or unstructured interviews. This method provides a platform for obtaining knowledge from experts who can either oppose or support the research findings. However, interviewees can only respond within their circumstances based on their personal experiences and knowledge, hence the need for special consideration in interviewee selection.

7.2 Validation Through SME Input Analysis

Mouton (2001) states that engagement with SMEs can be done using four different approaches, namely:

1. Free attitude interviews;
2. Telephonic interviews;
3. Semi-structured interviews;
4. Structured questionnaires.

This study will employ interviews with SMEs using telephonic interviews. Participants were prompted to answer a series of predetermined questions to allow for the analysis and interpretation of the collected evidence in a standard way.

A validation framework document, available in Appendix C, which summarised the findings from this study, served as a pre-read material for the SMEs to familiarise them with the study before the validation session. Afterwards, telephonic interviews and Microsoft teams meetings were conducted. In the interview, participants were required to validate the concepts identified, the concept categories, the proposed implementation framework and/or recommend improvements to the preliminary maintenance strategy implementation framework in the context of the Passenger Rail Agency of South Africa. After the completion of the validation session, the suggested improvements were incorporated into the maintenance strategy implementation framework to develop the final maintenance strategy implementation framework. The interviewees who participated in the SME input analysis were from diverse areas of expertise, as is detailed in Appendix D.

7.2.1 SME’s background—the interviewees

According to Creswell (2014), qualitative participants are identified by purposeful sampling based on merit as opposed to random sampling. The merit includes the participant’s expertise and knowledge applicable to the research topic which enables them to best assist the researcher concerning the research problem.

To holistically examine the research problem and to gain insightful feedback from the process, experts in railway maintenance were identified as SMEs. A summary of the SMEs’ backgrounds is given in Appendix D.

7.2.2 Interview questions

The telephonic and Microsoft teams in-depth interviews were of two kinds. Firstly, the focus was on the development of the framework. On this session, the interview questions focused on the identification of concepts, concept categorisation, the interaction between categories and the framework developed. The SME input analysis questions are shown in Appendix E.

Follow-up questions were based on the response from the interviewee. This helped to get much detail from the subject matter experts about determining the usefulness of the framework in the rolling stock maintenance.

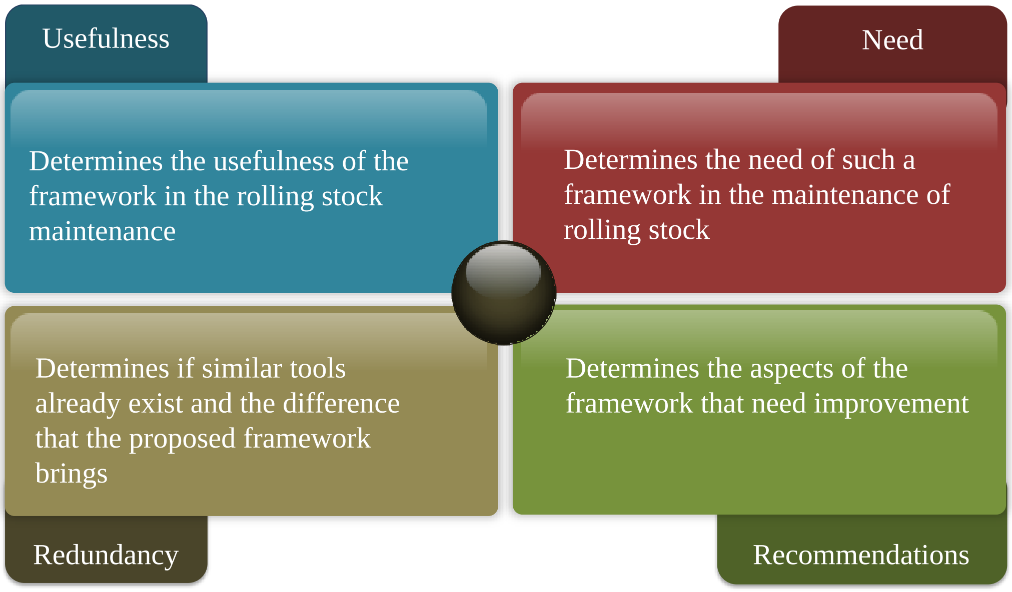

Figure 7.1: Aspects used for interview questions (adapted from Mouton, 2001; Creswell, 2014)

In the second phase, the interviewees were asked about the four aspects of the framework, namely usefulness, need, redundancy and recommendations as shown in Figure 7.1.

7.2.3 SME semi-structured interview feedback

As discussed, interviewees were also allowed to provide more detailed feedback through open questions. The responses received to the open questions are summarised in Table 7.1.

Table 7.1: SME semi-structured interview feedback (first phase)

Aspect	No	Feedback and updates necessary to the study
Identification of concepts	1	All the participants agreed that the identified concepts are relevant to rail maintenance to improve the availability of passenger rolling stock through maintenance strategy intervention. Participant P6 further argued that the most important aspect is how these concepts are implemented. Participants P1 and P2 raised issues with training of personnel on how frequently should they be conducted given the financial constraints. P2 further highlighted the need to maintain high quality

		especially when it comes to purchasing of spare parts.
	2	All the participants agreed that concepts were properly identified.
	3	Participants P1, P2, P3 added finances as another concept that should be added. The argument was that, without proper finances, any maintenance plans are futile. PRASA being an SOE, finances are mainly from the government. They further highlighted the need to have the procurement procedures expanded to include time frames and choice made on choosing the supplier. The rest of the participants were satisfied with the raised components.
Concept categories	4	All participants were satisfied with the categorisation of concepts and the different groups identified.
	5	All participants agreed that the categories covered the aspects of a maintenance strategy.
	6	No other category was proposed by the participants as they were satisfied by the ones proposed.
Interaction between categories	7	All participants agreed on the flow presented as it was in line with maintenance practices in the rail environment, particularly at PRASA.
	8	Participants agreed on the interaction of categories as shown in Figure 6.1: Interaction of categories.
	9	No necessary changes were proposed.
Framework developed	10	All the participants agreed that the proposed framework can be used to effectively implement the proactive maintenance strategy.

	11	Participants were happy with the inclusion of continuous improvement. This was because of the need to improve on any performed tasks. Participant P3 raised concerns on the continuous improvement on the given diagram not covering operation and maintenance requirements. Operation and maintenance requirements cover data acquisition and analysis, personnel and maintenance requirements.
	12	Participant P3 highlighted the need to clearly outline how benchmarking was to be done given the different dynamics of the organisation. P1, P2, P3 emphasised the need for availing finances for maintenance as its success hugely depends on the allocated funds. Participant P2 highlighted the need to introduce a feedback loop in the framework as it looked one-directional.

The second phase of SME interviews was conducted so as to give much focus on the framework proposed, to enable a critique of its usefulness, its need, redundancy and recommendation from subject matter experts. This was done because the framework was the main deliverable of the study.

Table 7.2: SME semi-structured interview feedback (second phase)

Aspect	Question	Feedback and updates necessary to the study
Usefulness	Is the framework useful in the rolling stock maintenance?	All the participants agreed that the proposed maintenance strategy implementation framework is useful in

		the rolling stock maintenance.
Need	Is PRASA in need of such a framework in the maintenance of rolling stock?	Participants highlighted that a framework of the nature as proposed was necessary. Participants P4 and P6 further highlighted the need for such a framework by stating that currently, PRASA does not follow any framework. Participant P6 further argued that if there was any then it should have been documented. Since there is no such document, it then means no such framework exists in the organisation. Participant P5 highlighted that the main problem faced by the organisation is lack of a clearly outlined and standardised document which can be followed in maintenance implementation. Hence, participants agreed on the need for a framework such as the one proposed.

Redundancy	Is there a similar framework at PRASA and if there is, what difference does the proposed framework bring?	As has been highlighted on the "Need" aspect, no implementation framework has been adopted by the organisation hence no redundancy exists.
Recommendation	Are there any aspects of the framework that need improvement?	Participants P1, P2 and P3 recommended that finances allocated to maintenance should be added within the framework. Participant P2 recommended the inclusion of a feedback loop so that the framework does not become one-directional.

7.2.4 SME input analysis conclusion

The input of subject matter experts indicates that participants were content with identified concepts, concept categories and interaction between concepts. A further probe was done on the proposed framework on aspects such as its usefulness, need and redundancy. The results show that participants were generally satisfied with the proposed maintenance strategy implementation framework. There was a general consensus that the proposed framework with the recommendations given, if properly followed, can increase the availability of rolling stock at the Passenger Rail Agency of South Africa.

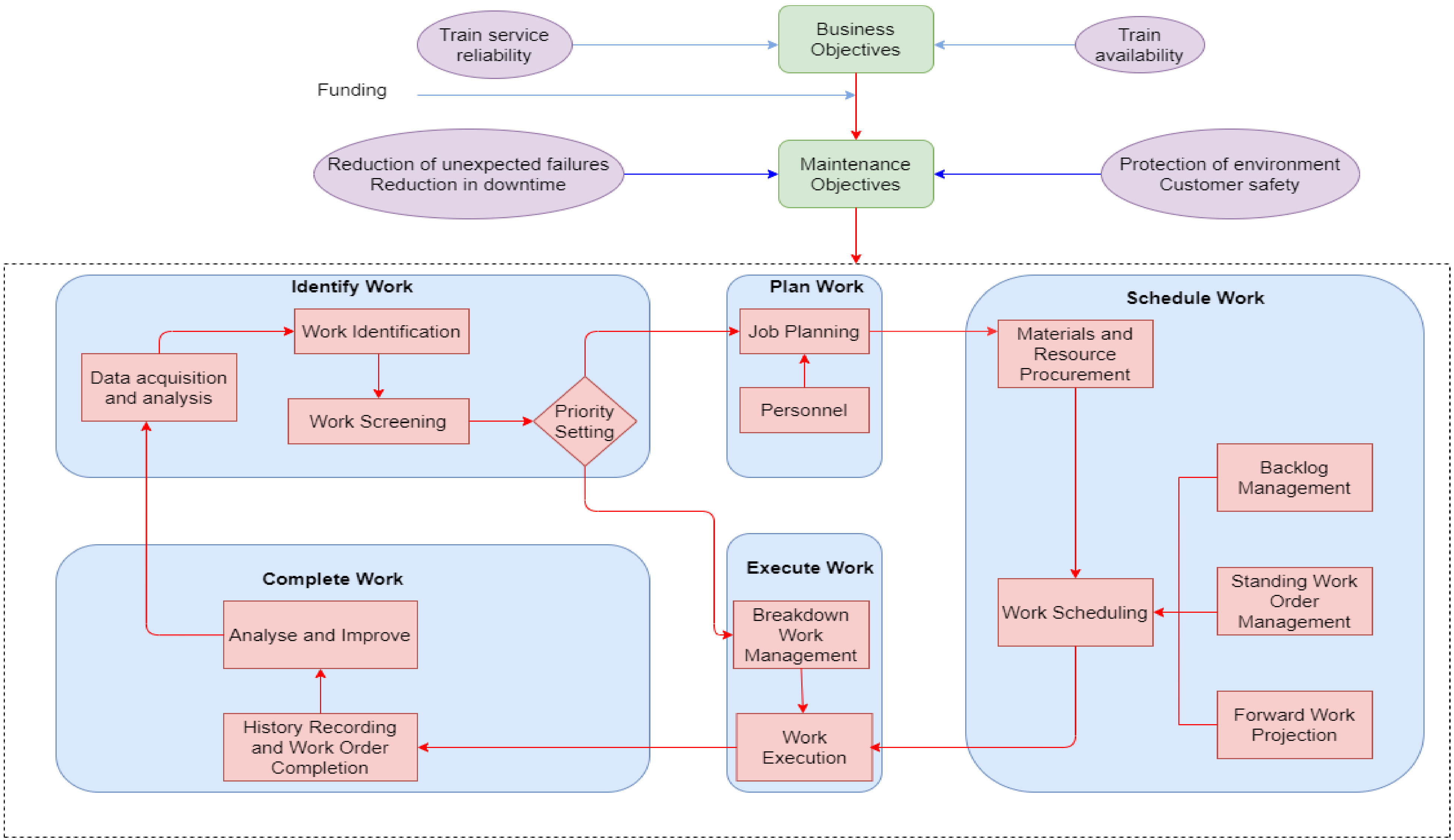

Figure 7.2: Validated maintenance strategy implementation framework

Use of the proposed maintenance strategy implementation can deliver a safer and more cost-effective work environment for asset-intensive businesses. The merits include an increase in availability, reliability, safety at the workplace (planned work is inherently safer to perform than unplanned tasks), labour productivity, ability to collect and analyse data for failure analysis/trend, accurate budget forecasting and the ability to measure workload and compliance to process.

The proposed framework starts with spelling out the business objectives of the organisation. At PRASA, the business objectives are to ensure train service reliability and train availability. These two objectives are closely tied to PRASA's income generation, hence they fall under business objectives. If one of the objectives is not met, PRASA's market share will drop as customers will move to alternative service providers. The business objectives are the same across all departments within the organisation. Each department then derives its departmental objectives from the business objectives.

PRASA, being a State Owned Enterprise (SOE), depends largely on the government for financial resources. However, this does not mean that PRASA does not get financial assistance from other stakeholders. These are important in meeting business objectives as they determine what the organisation can do. Departments then set their objectives based on their budget allocation.

From the business objectives, the next step is to derive maintenance objectives. As shown in the developed framework, for PRASA, these are the reduction of unexpected failures, reduction in downtime, customer safety and protection of the environment. These maintenance objectives help in achieving business objectives. If downtime is reduced, train service reliability and train availability increase. When travelling, customers prefer service providers who ensure their safety. To gain and maintain a large market share through maintenance, PRASA has to ensure that anything that poses a threat to customer safety is removed. These could include exposed wires, sharp components and spilt oil on surfaces among other safety threats.

Reduction in downtime will greatly increase train service availability with other factors remaining constant. As shown Figure 1.1, downtime is a major contributor to train service unavailability. Focusing on reducing downtime results in improvement of train availability. Normally, nations require organisations to protect the environment in which they operate and PRASA is no exception. One way in which PRASA can protect its environment is not to subject it to high level train noise. There is usually a noise limit which should not be exceeded. In this instance, ensuring train sets are properly maintained helps in reducing these noise levels.

The next step is to figure out how the maintenance objectives can be met. As shown in Figure 7.2, five phases are involved. These are to 'identify work', 'plan work', 'schedule work', 'execute work' and 'complete work'. If these phases are properly done, train service reliability will be increased, as well as train availability. According to the PRASA corporate plan, by end 2021, the organisation should be having 90 percent train availability.

In the 'identify work' phase, there is data acquisition and analysis, work identification, work screening and priority setting. Data acquisition and analysis involves the collection of data through conducting inspections and monitoring. Some of the data collected and analysed includes failure effect, failure rate, failure mode, operating time, legislation and rules. The collected data, together with historical data, is analysed to identify what needs to be done to meet the maintenance objectives. This is done to get full details of operation and equipment condition. From the analysis, work to be done is identified. The work will be based on the data analysed hence giving the condition of the rolling stock.

It might be too early to carry out some of the work identified or it may need to be done immediately. For this reason, work screening is done. The process of work screening is to determine jobs that can be part of the schedule. Given that the proposed framework advocates for condition-based maintenance, there is a need to eliminate unnecessary maintenance tasks. Unnecessary maintenance could be deteriorated components that can still operate properly and can be allowed to run without risk of them failing. These are therefore omitted from the current schedule to save resources. After work screening then the output (work necessary to be carried out) proceeds to priority setting.

Almost all Computerised Maintenance Management Systems (CMMS) contain a field where you can set the work order priority. As such PRASA should make use of CMMS. Work Order Priority is an indication of the level of business risk that relates to the fault or failure that the work order is intended to address. The higher the overall risk associated with the fault or failure, then the higher the priority. Risk is generally a combination of likelihood and consequence. Hence, when assessing priority work order in maintenance, PRASA should ask the following questions:

1. If the work is not done and the equipment suffers a functional failure, in what way would this impact on the achievement of the organisation's business objectives, and how large would that impact be?
2. If the work is not done, how likely would the equipment be to suffer that functional

failure within the next (predetermined) period?

The first question assesses the potential consequences of not performing the work and the second question assesses the likelihood of those consequences eventuating. These can then be combined in a risk matrix similar to the one shown in Figure 7.3.

The likelihood requires one to consistently identify in advance the period over which the likelihood of failure is to be assessed. PRASA can possibly do this through the data acquisition and analysis phase where different tasks such as monitoring and historical data analysis are done. Setting up of priorities requires knowledge of the technical condition of rolling stock, the deteriorating rate of components and the impact if failure occurs. It is often difficult for a single person to have full knowledge of these, so forming a team that consists of front-line supervisors from maintenance and production is recommended.

High priority order work should be prioritised first. However, it does not mean that such work will be executed before other jobs. High priority order work might need spare parts that need to be procured first. Therefore, this kind of work helps to identify which spare parts and tools should be resourced with urgency.

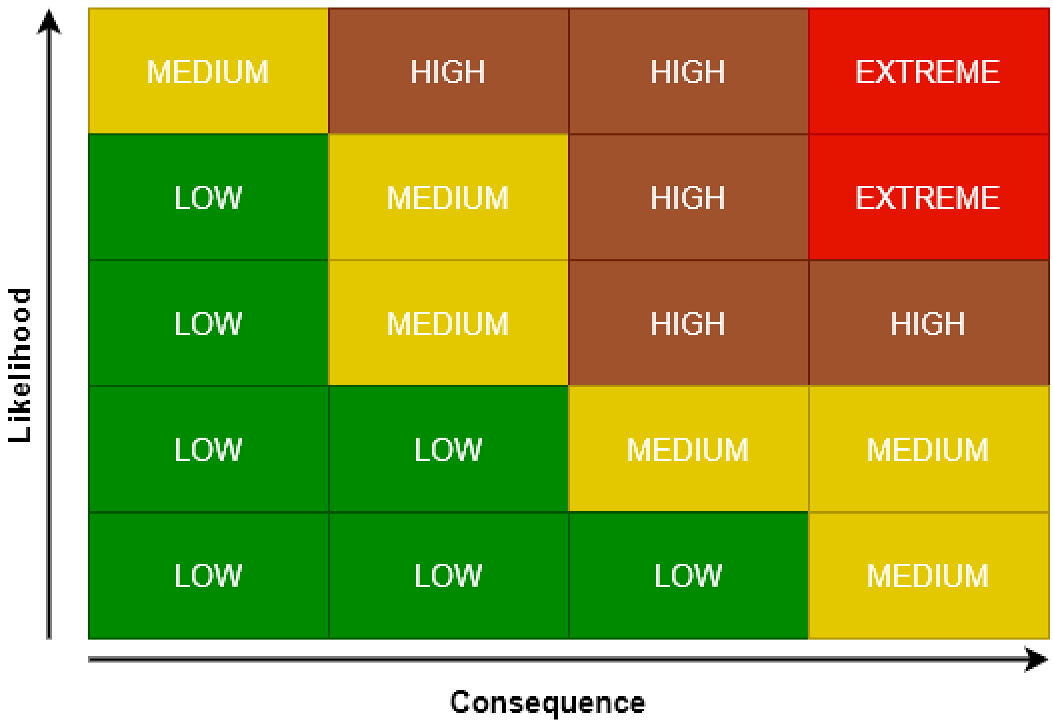

Figure 7.3: Risk matrix

The tasks that have gone through priority setting are the ones that will be on the 'execute work' phase. Before the work is executed, maintenance personnel need to plan. As seen from Figure

7.2, the ‘identify work’ phase is followed by a ‘plan work’ phase. The plan work phase consists of job planning and personnel. The personnel feeds the work to job planning. This shows that job planning is done after the personnel stage. Under personnel, when work to be done has been identified, maintenance personnel needed to perform such work are identified.

With the knowledge of work to be undertaken, maintenance personnel needed are selected based on their skills. Those with skills necessary for the job at hand are selected. Given the amount of job at hand, the number of personnel needed is established as well. Communication is made through the department of what needs to be done and management commitment is sought.

Under job planning, the type and number of tools and spare parts are determined. These are easily done by competent and trained personnel. Hence it is also established when resources and materials needed should be procured. At this stage, a decision on when the maintenance should be done is made. The following phase is ‘schedule work’.

Under the schedule work phase, the categories involved are materials and resource procurement, work scheduling, backlog management, standing work order management and forward work projection. The materials and resource procurement focus on what was identified in job planning. The exact type and quantity of both tools and spare parts needed for the jobs needed are procured. Parts and materials are one of the most important requirements in the implementation of the proposed framework. Given the importance of this, maintenance personnel at PRASA should ensure the availability of spare parts and other necessary materials all the time. Spare parts that are needed should be purchased early enough to avoid backlogs. Spare parts should conform to the quality standards of the organisation.

After the procurement of both tools (that may not be available) and spare parts, work scheduling is then done. Work scheduling is dependent on backlog management, standing work order management and forward work projection. The backlog is any work listed that has an execution date before today’s date. It is work that was not done. This category needs to be carefully analysed so that the list of work can be scheduled accordingly. Such work tasks will allocated a new priority. However, it is important to try to avoid backlogs.

The forward log is any work listed that has an execution date ahead of today’s date. This list will make up the major work in the scheduling. It is work that has arisen from data acquisition and analysis. The jobs in the forward log should be analysed properly for cost estimation and effective job execution. If the information is inadequate, more data should be collected and analysed before maintenance planning and execution can be carried out. Forward log jobs need to be executed as close to the date as possible. Therefore, if spare parts are needed, before scheduling the job, availability of these should be known.

The ‘execute work’ phase follows the schedule work phase. The execute work phase consists of breakdown work management and work execution. In this phase, work is broken down into small manageable tasks. This is done to enable simultaneous execution of work. An example is when wheelsets of a motor coach are to be maintained, the first step is to work on each wheelset separately, from each wheelset breakdown to bogies. Different tasks can be identified and those that can be done simultaneously can be done in that way. Breakdown work management helps in team assignments where a team can be assigned to perform some maintenance task. In the example of wheelsets, different teams can be assigned to different teams and within the team focusing on a specific wheelset, they can share responsibilities by assigning team members to different bogies. Breakdown maintenance helps also to reduce mean time to repair of components and as a result reduces the downtime of train sets.

After the breakdown of work, maintenance is then executed. Execution tasks depend on maintenance to be done. The execution tasks include replacing, repairing, cleaning, tightening, lubricating, adjustment, servicing and overhauling. These tasks should be performed by trained personnel. This will ensure quality rendering of maintenance. If maintenance tasks are not properly done, mean time before failure might be reduced significantly.

It is sometimes hard to visually appreciate how well a process is working unless some meaningful Key Performance Indicators are put in place. This is of importance to PRASA, having lost their quality certification. Key Performance Indicators help to focus on the barriers to process adoption that are preventing the achievement of good outcomes. Often there will be circumstances that will see a KPI measure go backwards rather than the desired direction but it will alert all concerned that there is an issue that needs to be fixed in order to move forward.

At the end of the process, under the ‘complete work’ phase, there should be analysis and improvement. It is part of the Continuous Improvement Process shown in Figure 6.2. Maintenance personnel need to analyse the work performed with responsible supervisors and immediately make changes where necessary. Performing the changes ensures that the tasks will be better executed the next time. Items that may need change after analysis include task duration, the quantity of materials, work steps out of sequence and labour requirements.

The output of the process, is that of sending the recorded history and work order completion to data acquisition and analysis in the ‘identify work’ phase. This helps so that it forms part of the new data for the next maintenance work. It provides an updated work on what has been done to the system in terms of maintenance and also provides an updated condition of train sets. This is further emphasised by the main feedback loop. The main feedback loop shows that the output data of the system becomes the input into the system.

7.3 CHAPTER SUMMARY

The chapter described and explained the method of validation that was carried out. Validation was done through subject matter expert opinion. Semi-structured questions and a pre-reading document were prepared. The pre-reading document was shared with SMEs weeks before conducting interviews. Interviews were conducted through telephone and Microsoft Teams depending on the preference of the interviewee. The first phase of the validation focused on the identification of concept, categorisation of concepts and interaction between categories. The maintenance strategy implementation framework was validated using SME input analysis through semi-structured interviews. Feedback from the SMEs was incorporated to develop the final maintenance strategy implementation framework shown in Figure 7.2.

In the second phase of validation, the main focus was on the framework itself as shown in Figure 6.3: Developed maintenance strategy framework. The focus was on the usefulness, need and redundancy of the framework. Based on the results of the SMEs opinions, the framework is useful to PRASA, there was a need for such a framework and no redundancy was found on the proposed framework. It is also concluded that the framework has the potential to contribute to enhancing improving the availability of rolling stock at the Passenger Rail Agency of South Africa.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

This chapter presents a summary of the research findings of each chapter. A discussion of the limitations and contributions of the study will also be presented followed by recommendations and future research based on the foundations laid in this study.

8.2 RESEARCH SUMMARY

The background, research aim and objectives, scope of the study, research design and methodology, and the validation strategy were presented in Chapter 1. Background of the research was provided by setting out the need for an effective maintenance strategy at Passenger Rail Agency of South Africa (PRASA). The first chapter highlighted the research questions and objectives. The objectives were strictly followed to address the problem at hand. The objectives included identifying different maintenance strategies, describing the influence of different maintenance strategies, assessing the methods used in measuring the influence of maintenance strategies, identifying maintenance concepts and proposing a maintenance strategy implementation framework.

Chapter 2 focused on conducting a comparative study of different maintenance strategies. These include run-to-failure, preventive and predictive maintenance strategies. The comparison was done by describing and explaining each maintenance strategy and its influence on the availability of equipment in a qualitative manner. The chapter also focused on unearthing ways of optimising maintenance strategies on implementation. Asset Maintenance Optimisation System (AMOS), focuses on the effectiveness and inspection of maintenance programmes. In such a condition, skills for inspection, procedure and any quality must be developed. In AMOS, the first stage encompasses the benchmarking process and management audit whilst the second phase based on the first phase comes up with a plan for the application of risk-based inspection and maintenance and planning tools. In trying to optimise maintenance strategies, maintenance personnel have to avoid carrying out imperfect maintenance.

The chapter also discussed different methods used in maintenance strategy selection. The selection of maintenance strategy for implementation is based on many factors such as tools, type of components, availability of skilled personnel, spare parts, applicability, safety, environmental problems, costs, mean time between failures, mean time to repair and managements' view. It also depends on the organisation's objectives. Proper selection of a maintenance strategy can result in many benefits such as the reduction in risks of fatal and or costly damages, savings through reduced maintenance costs, increase in customer satisfaction and increase in product quality.

Different barriers to maintenance management were identified. These include improper benchmarking, lack of communication and information, lack of measurement of overall equipment, poor teamwork, ineffective performance measures, unavailability of training, lack of empowerment, insufficient top management support, low employee commitment towards maintenance and lack of strategic planning and implementation.

Chapter 3 focused on the performance measurement system. This was done to investigate the ways that are currently being implemented in measuring the performance of maintenance strategies. Of note is the importance of the measuring system and the key performance indicators.

Chapter 4 was on the research methodology. The chapter was divided into different sections. These are research philosophy, research approach, research strategy, research methods, data collection and analysis, conceptual framework analysis and the evaluation process. Of note in data collection and analysis is the use of a systematic literature review.

Chapter 5 was used to describe and explain the maintenance depot (Rolling Stock division of the Metrorail, Salt River depot). The chapter gave the background to Metrorail, how rail transport started in South Africa and also the different types of train sets available. It further described train configuration at PRASA. One motor coach can sustain 4 passenger trailers, hence a complete configured train set consists of 12 passenger coaches and 3 motor coaches. The maintenance strategy currently employed at the selected maintenance depot was explained and time spent maintaining different strategies was established through historical data. The maintenance strategy comprises of three types of scheduled maintenance interventions or 'sheds' namely A-shed, B-shed and C-shed. These take 2 hours, 3 hours and 5 hours respectively.

Chapter 6 discussed the identification of different maintenance conceptual concepts. The concepts were then categorised into different groups. Categorising was based on similarity and being able to be done at the same time or enabling further implementation. The maintenance strategy implementation framework was then developed.

Chapter 7 covered the validation of the proposed maintenance strategy implementation framework. The validation was done through subject matter expert opinion. To accomplish this, in-depth telephonic interviews were conducted. The input of the SME helped to refine the developed framework.

8.3 Contribution To Literature And Practice

This research contributes to both the academic literature and the implementation of maintenance strategies in the rail environment. It adds to the body of literature by providing an example of how a mixed-methods approach can be applied to developing a framework to address a real-world operational problem. Literature had not provided clearly outlined maintenance strategy concepts and this study provides this. Finally, the framework itself constitutes a contribution to literature.

From this research, a paper has been written. It has since been accepted for publication in the journal of the South African Institute of Industrial Engineering. The paper is titled, "Maintenance strategies in the rail environment". Its main contribution is the maintenance strategy framework that was developed in this thesis.

In terms of contributions to practice, this study proposes a mechanism for effective implementation of a maintenance strategy particularly at the Passenger Rail Agency of South Africa (PRASA). This helps in the effective implementation of a maintenance strategy. As a result availability, reliability and customer satisfaction are bound to improve. No evidence of an existing maintenance implementation framework was found in PRASA documents on maintenance. The result was further approved by subject matter experts from PRASA when they agreed that there is no official maintenance strategy being used by the organisation. If there is no official maintenance strategy, then no maintenance strategy implementation framework can exist. This can be seen as one of the reasons for low train set availability. This research is therefore of utmost importance to practice as it provides a way of implementing a maintenance strategy through the proposed maintenance strategy implementation framework. The proposed framework is also flexible, in the sense that if there are any changes, for example, in the business objective, relevant changes on all the parts of the framework can easily be made.

8.4 Limitations Of The Study

The study was set within the rail maintenance environment. Particular attention was paid to passenger trains. The result is most relevant to such an environment and PRASA specifically.

It, however, leaves the proper use of the framework in the hands of maintenance personnel, such as the level of quality rendered on each aspect of the framework.

The study did not focus on other contributors to component failure. These include vandalism, as evidenced in the case at the PRASA Salt River depot. Vandalism is one of the contributors to rolling stock decline in availability. Due to the scope of the research, it was not considered. Other contributors are the quality of spare parts and tools and these too were not considered. The details of procurement, procedures to be followed, rules of worker unions and strikes, all of which play a part in maintenance implementation were not considered. This was because the focus of the study was on maintenance strategies.

8.5 Recommendations And Future Work

In conducting this research, recommendations and opportunities for future study were identified. These are detailed in the following sections.

8.5.1 Recommendations

In the use of the maintenance strategy implementation framework developed in the study, it is recommended that different aspects of the framework be followed diligently. All the concepts should be of high quality as a small deviation from the required level of quality might have an impact on the overall effectiveness of the maintenance strategy.

Finally, there seems to be uncertainty at PRASA on which maintenance strategy is being employed by the organisation. Some respondents argued that the different sheds discussed in section 5.4 are just a maintenance programme, while one participant argued that the organisation had decided to implement predictive maintenance, whether it is followed or not is a different case. There is thus a need to have all employees trained and educated on the maintenance strategy being employed by the organisation. This helps all to pull in one direction.

8.5.2 Future Work

Future research should focus on the tender process, the effect of other departments, refurbishment programmes and vandalism. These all have an effect on the overall availability of rolling stock. It is important to establish effective ways in which they should be handled. The research did not consider the relationships of the five phases namely identify work, plan work, schedule work, execute work and complete work. Improvement of this work could be focusing on the relationship of these phases. A closer look can be done within the phases themselves as well. On the identify work phase, the relationships between data acquisition and analysis, and work identification can be established. Relationship between work identification and work screening can be done, as well as on work screening and priority setting. The same can also be done with other phases. In establishing these relationships, causal relationship techniques can be used.

The research focused on PRASA in the Western Cape province. More work can be done to include other provinces since PRASA is not confined to the Western Cape. Some of the regions might be experiencing different dynamics from those in the Western Cape hence the need to carry out similar research in other regions.

Chapter 9 REFERENCES

Afefy, I. H. (2010) 'Reliability-Centered Maintenance Methodology and Application: A Case Study', *Engineering*, 02(11), pp. 863–873. doi: 10.4236/eng.2010.211109.

Aju kumar, V. N., Gupta, P. and Gandhi, O. P. (2019) 'Maintenance performance evaluation using an integrated approach of graph theory, ISM and matrix method', *International Journal of Systems Assurance Engineering and Management*. Springer India, 10(1), pp. 57–82. doi: 10.1007/s13198-018-0753-6.

Alabdulkarim, A. A., Ball, P. D. and Tiwari, A. (2014a) 'Influence of resources on maintenance operations with different asset monitoring levels: A simulation approach', *Business Process Management Journal*, 20(2), pp. 195–212. doi: 10.1108/BPMJ-12-2012-0135.

Alabdulkarim, A. A., Ball, P. D. and Tiwari, A. (2014b) 'Influence of resources on maintenance operations with different asset monitoring levels: A simulation approach', *Business Process Management Journal*, 20(2), pp. 195–212. doi: 10.1108/BPMJ-12-2012-0135.

Alaswad, S. and Xiang, Y. (2017) 'A review on condition-based maintenance optimization models for stochastically deteriorating system', *Reliability Engineering and System Safety*. Elsevier, 157, pp. 54–63. doi: 10.1016/j.ress.2016.08.009.

Andrés, J., Cadarso, L. and Marín, Á. (2015) 'Maintenance scheduling in rolling stock circulations in rapid transit networks', *Transportation Research Procedia*. Elsevier B.V., 10(July), pp. 524–533. doi: 10.1016/j.trpro.2015.09.006.

Argyropoulou, K., Iliopoulou, C. and Kepaptsoglou, K. (2018) 'Model for Corrective Maintenance Scheduling of Rail Transit Networks: Application to Athens Metro', *Journal of Infrastructure Systems*, 25(1), p. 04018035. doi: 10.1061/(asce)is.1943-555x.0000457.

Arunraj, N. S. and Maiti, J. (2007) 'Risk-based maintenance-Techniques and applications', *Journal of Hazardous Materials*, 142(3), pp. 653–661. doi: 10.1016/j.jhazmat.2006.06.069.

Asekun, O. O. and Fourie, C. J. (2015) 'Selection of a decision model for rolling stock maintenance scheduling', *South African Journal of Industrial Engineering*, 26(1), pp. 135–149. doi: 10.7166/26-1-1068.

Asset, T. and Plan, M. (2020) 'Scc tamp'.

Bazrafshan, M. and Hajjari, T. (2012) ‘Diagnosing maintenance system problems: Theory and a case study’, *Quality and Reliability Engineering International*, 28(6), pp. 594–603. doi: 10.1002/qre.1459.

Bengtsson, M. (2014) ‘Condition Based Maintenance in Technical Systems’, pp. 1–17.

Bertolini, M. and Bevilacqua, M. (2006) ‘A combined goal programming - AHP approach to maintenance selection problem’, *Reliability Engineering and System Safety*, 91(7), pp. 839–848. doi: 10.1016/j.ress.2005.08.006.

Bevilacqua, M. and Braglia, M. (2000) ‘Analytic hierarchy process applied to maintenance strategy selection’, *Reliability Engineering and System Safety*, 70(1), pp. 71–83. doi: 10.1016/S0951-8320(00)00047-8.

Bramer, M. (2016) ‘Measuring the Performance of a Classifier’, 23(3), pp. 175–187. doi: 10.1007/978-1-4471-7307-6_12.

Bryman. (2014) ‘Formulating a Proposal and Reviewing the Literature’, in *Research Methodology*, pp. 95–96.

Bryman, B. (2014) *Research Methodology: Business and Management Contexts*. Oxford University Press.

Budai, G., Dekker, R. and Kaymak, U. (2009) ‘Genetic and memetic algorithms for scheduling railway maintenance activities’, *Erasmus University Rotterdam*, No. EI 200, pp. 1–23.

Budai, G., Huisman, D. and Dekker, R. (2006) ‘Scheduling preventive railway maintenance activities’, *Journal of the Operational Research Society*, 57(9), pp. 1035–1044. doi: 10.1057/palgrave.jors.2602085.

Caldera, H. T. S., Desha, C. and Dawes, L. (2017) ‘Exploring the role of lean thinking in sustainable business practice: A systematic literature review’, *Journal of Cleaner Production*, 167(June 2019), pp. 1546–1565. doi: 10.1016/j.jclepro.2017.05.126.

Cane, J. B. (2011) ‘Performance Improvement through an Asset Maintenance Optimisation System’, *Applied Sciences*, 11(9), pp. 1580–1586.

Carannante, T. (2002) ‘Total Productive Maintenance (TPM) - Part 4’, *Foundryman*, 95(7), p. 261.

Carretero, J. (2003) ‘Applying RCM in large scale systems: A case study with railway networks’, *Reliability Engineering and System Safety*, 82(3), pp. 257–273. doi: 10.1016/S0951-8320(03)00167-4.

Chaïb, R. (2014) ‘Failure: A source of progress in maintenance and design’, *Physics Procedia*. Elsevier B.V., 55(December), pp. 185–191. doi: 10.1016/j.phpro.2014.07.027.

Conradie, P. D. F. (2015) ‘Quantifying system reliability in rail transportation in an ageing fleet environment’, *South African Journal of Industrial Engineering*, 26(2), pp. 128–142. doi: 10.7166/26-2-1076.

Crespo Marquez, A. and Gupta, J. N. D. (2006) ‘Contemporary maintenance management: Process, framework and supporting pillars’, *Omega*, 34(3), pp. 313–326. doi: 10.1016/j.omega.2004.11.003.

Creswell, J. (2014) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 4th edn. SAGE Publications Inc.

Cromie, S. (2015) ‘Integrating human factors training into safety management and risk management: A case study from aviation maintenance’, *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 229(3), pp. 266–274. doi: 10.1177/1748006X15572498.

Department of Transport (2005) ‘KEY RESULTS OF THE NATIONAL HOUSEHOLD TRAVEL SURVEY: The First South African National Household Travel Survey 2003 TITLE : Key Results of the National Household Travel Survey’, pp. 15–36.

Dhillon, B. (2010) ‘Human Error in Maintenance’, *Human Reliability, Error, and Human Factors in Engineering Maintenance*, pp. 63–77. doi: 10.1201/9781439803844.ch5.

Do, P. (2015) ‘A proactive condition-based maintenance strategy with both perfect and imperfect maintenance actions’, *Reliability Engineering and System Safety*. Elsevier, 133, pp. 22–32. doi: 10.1016/j.ress.2014.08.011.

Dudovskiy, J (2018) ‘The Ultimate Guide to Writing a Dissertation in Business Studies: A Step-by-Step Assistance’. Available at: https://research-methodology.net/about-us/ebook/.Accessed on 20 January 2020.

Dudovskiy, John (2018) *The Ultimate Guide to Writing a Dissertation in Business Studies: A Step-by-Step Assistance*.

Duran, O., Capaldo, A. and Acevedo, P. A. D. (2017) 'Lean maintenance applied to improve maintenance efficiency in thermoelectric power plants', *Energies*, 10(10), pp. 1–21. doi: 10.3390/en10101653.

Elsayed EA (2012) 'Reliability engineering', *Hoboken: John Wiley and Sons Inc Publishing*.

Emmert, P., Brooks, W. D. and Lurdick, R. G. (1971) *Books on Research Methods, Communication Booknotes*. doi: 10.1080/10948007109489547.

Espling, U. (2007) 'Maintenance Strategy for a Railway Infrastructure in a Regulated Environment', p. 171.

Eti, M. C., Ogaji, S. O. T. and Probert, S. D. (2006a) 'Development and implementation of preventive-maintenance practices in Nigerian industries', *Applied Energy*, 83(10), pp. 1163–1179. doi: 10.1016/j.apenergy.2006.01.001.

Eti, M. C., Ogaji, S. O. T. and Probert, S. D. (2006b) 'Reducing the cost of preventive maintenance (PM) through adopting a proactive reliability-focused culture', *Applied Energy*, 83(11), pp. 1235–1248. doi: 10.1016/j.apenergy.2006.01.002.

Eti, Mark C., Ogaji, S. O. T. and Probert, S. D. (2006) 'Strategic maintenance-management in Nigerian industries', *Applied Energy*, 83(3), pp. 211–227. doi: 10.1016/j.apenergy.2005.02.004.

De Felice, F. and Petrillo, A. (2011) 'Methodological approach for performing human reliability and error analysis in railway transportation system', *International Journal of Engineering and Technology*, 3(5), pp. 341–353.

Gandhare, B. S., Akarte, M. M. and Patil, P. P. (2018) 'Maintenance performance measurement - A case of the sugar industry', *Journal of Quality in Maintenance Engineering*, 24(1), pp. 79–100. doi: 10.1108/JQME-07-2016-0031.

Garg, A. and Deshmukh, S. G. (2006) 'Maintenance management: Literature review and directions', *Journal of Quality in Maintenance Engineering*, 12(3), pp. 205–238. doi: 10.1108/13552510610685075.

Goddard, W. and Melville, S. (2004) *Research Methodology: An Introduction*. 2nd editio. New Jersey, Blackwell Publishing.

Gomes, C. F. and Yasin, M. M. (2011) 'A literature review of maintenance performance measurement : A conceptual framework and directions for future research', (May 2014). doi:

10.1108/13552511111134565.

Gondal, U. H., Shahbaz, M. and Shahbaz, M. (2012) 'Interdepartmental Communication Increases Organizational Performance Keeping HRM as a Mediating Variable', *Asian Economic and Social Society*, 2(6), pp. 127–141.

Gulati, P. (2009) 'Research Management', *Fundamental and Applied Research*.

He, K., Maillart, L. M. and Prokopyev, O. A. (2015) 'Scheduling Preventive Maintenance as a Function of an Imperfect Inspection Interval', *IEEE Transactions on Reliability*. IEEE, 64(3), pp. 983–997. doi: 10.1109/TR.2015.2417153.

Horner, R.M.W.; EL-Haram, M A; Munns, A. (1997) 'Building maintenance strategy : a new management approach', *Journal of Quality in Maintenance Engineering; Bradford*, 3(4), pp. 273–280.

Irajpour, A. (2014) 'A Framework to Determine the Effectiveness of Maintenance Strategies Lean Thinking Approach', 2014.

Jabareen, Y. (2009) 'Building a Conceptual Framework: Philosophy, Definitions, and Procedure', *International Journal of Qualitative Methods*, 8(4), pp. 49–62. doi: 10.1177/160940690900800406.

Jackson, N. C. (2004) 'Background to Systematic Reviews', in *Handbook - systematic review of health promotion and public health interventions*. Cochrane, pp. 5–8.

Jardine, A. K. S., Lin, D. and Banjevic, D. (2006) 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', *Mechanical Systems and Signal Processing*, 20(7), pp. 1483–1510. doi: 10.1016/j.ymssp.2005.09.012.

Ji, B.. (2017) 'A Component Selection Method for Prioritized Predictive Maintenance', *IFIP Advances in Information and Communication Technology*, 513, pp. 433–440. doi: 10.1007/978-3-319-66923-6_51.

Johansson, J. and Rudberg, M. (2010) 'Maintenance management in process industries: mapping current practices', *Proceedings of the 17th EurOMA conference*, (May), pp. 1–10.

de Jonge, B., Teunter, R. and Tinga, T. (2017) 'The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance', *Reliability Engineering and System Safety*. Elsevier, 158(October 2016), pp. 21–30. doi: 10.1016/j.ress.2016.10.002.

Jonsson, P. (1997) 'The status of maintenance management in Swedish manufacturing firms', *Journal of Quality in Maintenance Engineering*, 3(4), pp. 233–258. doi: 10.1108/13552519710176863.

Journal, T. and Oct, N. (2007) 'Scheduling of Railway Track Maintenance Activities and Crews A . Higgins', 49(10), pp. 1026–1033.

Kang, N. (2016) 'A Hierarchical structure of key performance indicators for operation management and continuous improvement in production systems', *International Journal of Production Research*. Taylor & Francis, 54(21), pp. 6333–6350. doi: 10.1080/00207543.2015.1136082.

Karunakaran, S. (2016) 'Innovative application of LSS in aircraft maintenance environment', *International Journal of Lean Six Sigma*, 7(1), pp. 85–108. doi: 10.1108/IJLSS-01-2015-0001.

Keele and Staffs (2007) 'Guidelines for performing systematic literature reviews in software engineering'. EBSE Technical Report.

Kelly, A. (2006) *Strategic maintenance planning*. Oxford: Elsevier.

Kothari, C. . (2004) 'Research Methodology: Methods & Techniques', *New Age International (P) Ltd*. Available at: https://doi.org/10.1017/CBO9781107415324.004.

Krishnasamy, L., Khan, F. and Haddara, M. (2005) 'Development of a risk-based maintenance (RBM) strategy for a power-generating plant', *Journal of Loss Prevention in the Process Industries*, 18(2), pp. 69–81. doi: 10.1016/j.jlp.2005.01.002.

Ku, S. and Kim, C. (2019) 'Development of a model for maintenance performance measurement: A case study of a gas terminal', *Journal of Quality in Maintenance Engineering*. doi: 10.1108/JQME-07-2018-0060.

Kumar, U. (2013a) 'Maintenance performance metrics: A state-of-the-art review', *Journal of Quality in Maintenance Engineering*, 19(3), pp. 233–277. doi: 10.1108/JQME-05-2013-0029.

Kumar, U. (2013b) 'Maintenance performance metrics: A state-of-the-art review', *Journal of Quality in Maintenance Engineering*, 19(3), pp. 233–277. doi: 10.1108/JQME-05-2013-0029.

Kurt, M. and Kharoufeh, J. P. (2010) 'Optimally maintaining a Markovian deteriorating system with limited imperfect repairs', *European Journal of Operational Research*. Elsevier B.V., 205(2), pp. 368–380. doi: 10.1016/j.ejor.2010.01.009.

Laura, S. (2001) 'Linking maintenance strategies to performance', *International Journal of Production Economics*, 70(3), pp. 237–244. Available at: http://www.sciencedirect.com/science/article/pii/S0925527300000670.

Li, C. (2017) 'An overview: modern techniques for railway vehicle on-board health monitoring systems', *Vehicle System Dynamics*, 55(7), pp. 1045–1070. doi: 10.1080/00423114.2017.1296963.

Lin, J., Pulido, J. and Asplund, M. (2015) 'Reliability analysis for preventive maintenance based on classical and Bayesian semi-parametric degradation approaches using locomotive wheel-sets as a case study', *Reliability Engineering and System Safety*. Elsevier, 134, pp. 143–156. doi: 10.1016/j.ress.2014.10.011.

Lobna, K., Mounir, B. and Hichem, K. (2013) 'Using the ECOGRAI method for performance evaluation in maintenance process', *2013 International Conference on Advanced Logistics and Transport, ICALT 2013*. IEEE, pp. 382–387. doi: 10.1109/ICAdLT.2013.6568489.

Luan, X. (2017) 'Integrated optimization on train scheduling and preventive maintenance time slots planning', *Transportation Research Part C: Emerging Technologies*, 80, pp. 329–359. doi: 10.1016/j.trc.2017.04.010.

Lundgren, C., Skoogh, A. and Bokrantz, J. (2018) 'Quantifying the Effects of Maintenance - A Literature Review of Maintenance Models', *Procedia CIRP*. Elsevier B.V., 72, pp. 1305–1310. doi: 10.1016/j.procir.2018.03.175.

Makasheva, S. I. (2016) 'An automated monitoring system as an instrument of lean production of a traction power supply system', *Russian Electrical Engineering*, 87(2), pp. 107–109. doi: 10.3103/S1068371216020139.

Marcus, B. (2002) 'Condition Based Maintenance on Rail Vehicles–Possibilities for a more effective maintenance strategy'.

Maree, K. (2012) *First steps in research*.

Maróti, G. and Kroon, L. (2007) 'Maintenance routing for train units: The interchange model', *Computers and Operations Research*, 34(4), pp. 1121–1140. doi: 10.1016/j.cor.2005.05.026.

Matsapola, S. D. (2018) 'An investigation into the effectiveness of condition based maintenance for rolling stock vehicles in South Africa', 0002(August).

Mckone, K. E., Schroeder, R. G. and Cua, K. O. (2001) 'The impact of total productive maintenance practices on manufacturing performance', 19, pp. 39–58.

Mishra, R. P. (2015a) 'Development of a framework for implementation of world-class maintenance systems using interpretive structural modeling approach', in *Procedia CIRP*. doi: 10.1016/j.procir.2014.07.174.

Mishra, R. P. (2015b) 'Development of a framework for implementation of world-class maintenance systems using interpretive structural modeling approach', *Procedia CIRP*. Elsevier B.V., 26, pp. 424–429. doi: 10.1016/j.procir.2014.07.174.

Mitchell, B. F. (1995) 'Predictive Maintenance Program Evolution - Lessons Learned', pp. 7–10.

Morant, A., Larsson-Kråik, P. O. and Kumar, U. (2016) 'Data-driven model for maintenance decision support: A case study of railway signalling systems', *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 230(1), pp. 220–234. doi: 10.1177/0954409714533680.

Mouton, J. (2001) 'How to succeed in your master's and doctoral studies : a South African guide and resource book'.

Muchiri, P. (2011) 'Development of maintenance function performance measurement framework and indicators', *International Journal of Production Economics*. Elsevier, 131(1), pp. 295–302. doi: 10.1016/j.ijpe.2010.04.039.

Naji, A. (2018) 'Qualitative study on maintenance management in Moroccan industries', *IOP Conference Series: Materials Science and Engineering*, 351(1). doi: 10.1088/1757-899X/351/1/012012.

Nappi, R. (2014) 'Integrated Maintenance: analysis and perspective of innovation in railway sector', pp. 1–7. Available at: http://arxiv.org/abs/1404.7560.

Nazeri, A. and Naderikia, R. (2017) 'A new fuzzy approach to identify the critical risk factors in maintenance management', *International Journal of Advanced Manufacturing Technology*. The International Journal of Advanced Manufacturing Technology, 92(9–12), pp. 3749–3783. doi: 10.1007/s00170-017-0222-4.

Ohunakin, O. S. and Leramo, R. O. (2012) 'Total productive maintenance implementation in a beverage industry: A case study', *Journal of Engineering and Applied Sciences*, 7(2), pp.

128–133. doi: 10.3923/jeasci.2012.128.133.

Organ, M. (1997) ‘Avaliability-based maintenance within an asset management programme’.

Parida, A. (2015) *Performance measurement and management for maintenance: A literature review*, *Journal of Quality in Maintenance Engineering*. doi: 10.1108/JQME-10-2013-0067.

Patidar, L., Soni, V. K. and Soni, P. K. (2017) ‘Maintenance strategies and their combine impact on manufacturing performance’, *International Journal of Mechanical and Production Engineering Research and Development*, 7(1), pp. 13–22.

Peach, R., Ellis, H. and Visser, J. K. (2016) ‘A maintenance performance measurement framework that includes maintenance human factors: A case study from the electricity transmission industry’, *South African Journal of Industrial Engineering*, 27(2), pp. 177–189. doi: 10.7166/XX-X-1492.

Peng, F. (2011) ‘A Heuristic Approach to the Railroad Track Maintenance Scheduling Problem’, *Computer-Aided Civil and Infrastructure Engineering*, 26(2), pp. 129–145. doi: 10.1111/j.1467-8667.2010.00670.x.

Petticrew. (2006) ‘Systematic Reviews in the Social Sciences: A Practical Guide’. Blackwell Publishing.

Phogat, S. and Gupta, A. K. (2017) ‘Identification of problems in maintenance operations and comparison with manufacturing operations: A review’, *Journal of Quality in Maintenance Engineering*, 23(2), pp. 226–238. doi: 10.1108/JQME-06-2016-0027.

Picknell, J. V and Campbell, J. D. (1999) *Is RCM the right tool for you?*, *Plant Engineering*.

Van de Pieterman, R. P. (2011) ‘Optimisation of maintenance strategies for offshore wind farms’, *The offshore conference*, (December), pp. 1–12. Available at: https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-M--11-103.

Pintelon, L. and Parodi-herz, A. (2008) ‘Complex System Maintenance Handbook’, *Complex System Maintenance Handbook*, (January 2008). doi: 10.1007/978-1-84800-011-7.

Pintelon LM, G. L. (1992) ‘Maintenance management decision making’, *European Journal of Operational Research*, 3(58), pp. 301–317.

Plan, P. C. (2019) ‘Prasa corporate plan | mtef 2019/2021 1’, pp. 1–80.

Pogačnik, B., Tavčar, J. and Duhovnik, J. (2015) ‘Application of lean methods into aircraft maintenance processes', *Advances in Transdisciplinary Engineering*, 2, pp. 259–268. doi: 10.3233/978-1-61499-544-9-259.

Pombo, J. (2010) 'A Railway Wheel Wear Prediction Tool Based', *Journal of Theoretical and Applied Mechanics*, 48(3), pp. 751–770.

Rana, A. and Koroitamana, E. V. M. (2018) 'Measuring maintenance activity effectiveness', *Journal of Quality in Maintenance Engineering*, 24(4), pp. 437–448. doi: 10.1108/JQME-11-2016-0061.

Raouf, A.. (2006) 'Evaluating the effectiveness of maintenance strategies', *Journal of Quality in Maintenance Engineering*, 12(1), pp. 7–20. doi: 10.1108/13552510610654501.

Rausand, M. (1998) 'Reliability Centered Maintenance', *Reliability Engineering and System Safety*, 60, pp. 121–132.

Ravi, N. N., Mohd Drus, S. and Krishnan, P. S. (2019) 'Data mining techniques for transformer failure prediction model: A systematic literature review', *ISCAIE 2019 - 2019 IEEE Symposium on Computer Applications and Industrial Electronics*. IEEE, pp. 305–309. doi: 10.1109/ISCAIE.2019.8743987.

Rezvanizaniani, S. M. *et al.* (2008) 'Reliability Centered Maintenance for rolling stock: A case study in coaches' wheel sets of passenger trains of Iranian railway', *2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2008*. IEEE, pp. 516–520. doi: 10.1109/IEEM.2008.4737922.

Rezvanizaniani, S. M.. (2009) 'Reliability analysis of the rolling stock industry: A case study', *International Journal of Performability Engineering*, 5(2), pp. 167–175.

Rezvanizaniani, S. M., Barabady, J. and Kumar, U. (2009) 'Reliability analysis of the rolling stock industry : A case study Reliability Analysis of the Rolling Stock Industry : A Case Study', (January).

Rijsdijk, C. and Tinga, T. (2016) 'Observing the effect of a policy: A maintenance case', *Journal of Quality in Maintenance Engineering*, 22(3), pp. 277–301. doi: 10.1108/JQME-10-2014-0055.

Roger, M. (2011) 'University of Huddersfield Repository Creep force estimation at the wheel-rail interface Original Citation Ward , C . P ., Goodall , Roger M . and Dixon , R . (2011) Creep force estimation at the wheel-rail interface . In : 22nd International Symposium'.

S.Nakajima (1988) 'Introduction to TPM: Total Productive Maintenance.pdf', *Productivity Press, Cambridge*, p. MA. doi: http://www.plant-maintenance.com/articles/tpm_intro.shtml.

Sahoo, S. (2019) 'Assessment of TPM and TQM practices on business performance: a multi-sector analysis', *Journal of Quality in Maintenance Engineering*, 25(3), pp. 412–434. doi: 10.1108/JQME-06-2018-0048.

Ben Said, A. (2016) 'Experts' knowledge renewal and maintenance actions effectiveness in high-mix low-volume industries, using Bayesian approach', *Cognition, Technology and Work*, 18(1), pp. 193–213. doi: 10.1007/s10111-015-0354-y.

Sainz, J. A. and Sebastián, M. A. (2013) 'Methodology for the maintenance centered on the reliability on facilities of low accessibility', *Procedia Engineering*. Elsevier B.V., 63, pp. 852–860. doi: 10.1016/j.proeng.2013.08.279.

Saunders, M., Lewis, P. and Thornhill, A. (2007) *Research Methods for business students*. Fourth Edi. London: Prentice Hall.

Saunders, M., Lewis, P. and Thornhill, A. (2009) *Research Methods for Business Students*.

Saunders, M., Lewis, P. and Thornhill, A. (2012) *Research methods for business students*. 6th editio. Pearson Education.

Schlake, B. (2010) 'Impact of Automated Condition Monitoring Technologies on Railroad Safety and Efficiency', (217).

Schlake, B. W., Barkan, C. P. L. and Edwards, J. R. (2011) 'Train delay and economic impact of in-service failures of railroad rolling stock', *Transportation Research Record*, (2261), pp. 124–133. doi: 10.3141/2261-14.

Seecharan, T., Labib, A. and Jardine, A. (2018) 'Maintenance strategies: Decision Making Grid vs Jack-Knife Diagram', *Journal of Quality in Maintenance Engineering*, 24(1), pp. 61–78. doi: 10.1108/JQME-06-2016-0023.

Selcuk, S. (2017) 'Predictive maintenance, its implementation and latest trends', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 231(9), pp. 1670–1679. doi: 10.1177/0954405415601640.

Semma, E. M., Mousrij, A. and Gziri, H. (2018) 'Preliminary study of the vibration-based maintenance implementation: case study', *Journal of Quality in Maintenance Engineering*, 24(2), pp. 134–151. doi: 10.1108/JQME-10-2016-0047.

Shafiee, M. (2019) ‘Maintenance strategy selection for multi-component systems using a combined analytic network process and cost-risk criticality model’, *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 233(2), pp. 89–104. doi: 10.1177/1748006X17712071.

Shou, W.. (2019) ‘Value adding and non-value adding activities in turnaround maintenance process: classification, validation, and benefits’, *Production Planning and Control*. Taylor & Francis, 31(1), pp. 60–77. doi: 10.1080/09537287.2019.1629038.

Silonen, A. (2011) ‘Strategic maintenance improvement: driving forces and obstacles’, in *5th World Congress on Engineering Asset Management*. Brisbane.

Singh, R. (2013) ‘Total productive maintenance (TPM) implementation in a machine shop: A case study’, *Procedia Engineering*. Elsevier B.V., 51(May 2014), pp. 592–599. doi: 10.1016/j.proeng.2013.01.084.

Singh, R. K., Gupta, A. K. A., (2016) ‘Identification of problems in maintenance operations and comparison with manufacturing operations: A review’, *Journal of Quality in Maintenance Engineering*. IEEE, 23(1), pp. 226–238. doi: 10.1108/JQME-06-2016-0027.

Singh, R. K., Gupta, A.,. (2016a) ‘Ranking of barriers for effective maintenance by using TOPSIS approach’, *Journal of Quality in Maintenance Engineering*, 22(1), pp. 18–34. doi: 10.1108/JQME-02-2015-0009.

Singh, R. K., Gupta, A.. (2016b) ‘Ranking of barriers for effective maintenance by using TOPSIS approach’, *Journal of Quality in Maintenance Engineering*, 22(1), pp. 18–34. doi: 10.1108/JQME-02-2015-0009.

Skarlatos, D., Karakasis, K. and Trochidis, A. (2004) ‘Railway wheel fault diagnosis using a fuzzy-logic method’, *Applied Acoustics*, 65(10), pp. 951–966. doi: 10.1016/j.apacoust.2004.04.003.

Söderholm, P. and Nilsen, T. (2017) ‘Systematic risk-Analysis to support a living maintenance programme for railway infrastructure’, *Journal of Quality in Maintenance Engineering*, 23(3), pp. 326–340. doi: 10.1108/JQME-09-2016-0042.

Soh, S. S., Radzi, N. H. M. and Haron, H. (2012) ‘Review on scheduling techniques of preventive maintenance activities of railway’, *Proceedings of International Conference on Computational Intelligence, Modelling and Simulation*. IEEE, pp. 310–315. doi: 10.1109/CIMSim.2012.56.

Solomon, J, Rail, T. F. (2012) 'Transforming Condition Data into Maintenance Information.'

Sriskandarajah, C., Jardine, A. K. S. and Chan, C. K. (1998) 'Maintenance scheduling of rolling stock using a genetic algorithm', *Journal of the Operational Research Society*, 49(11), pp. 1130–1145. doi: 10.1057/palgrave.jors.2600627.

Stenström, C.. (2016) 'Preventive and corrective maintenance – cost comparison and cost–benefit analysis', *Structure and Infrastructure Engineering*. Taylor & Francis, 12(5), pp. 603–617. doi: 10.1080/15732479.2015.1032983.

Stratman, B., Liu, Y. and Mahadevan, S. (2007) 'Structural health monitoring of railroad wheels using wheel impact load detectors', *Journal of Failure Analysis and Prevention*, 7(3), pp. 218–225. doi: 10.1007/s11668-007-9043-3.

Thapa, R., Saldanha, S. and Prakash, R. (2018) 'Application of Lean Six-Sigma Approach To Reduce Biomedical Equipments Breakdown Time and Associated Defects', *Journal of Evolution of Medical and Dental Sciences*, 7(34), pp. 3771–3779. doi: 10.14260/jemds/2018/847.

Tongco, M. D. C. (2007) 'Purposive Sampling as a Tool for Informant Selection. A Journal for Plant, People and Applied Research', *Ethnobotany Research and applications*, 5, pp. 147–158. doi: 10.17348/era.5.0.147-158.

Turabimana, P. and Nkundineza, C. (2020) 'Development of an on-board measurement system for railway vehicle wheel flange wear', *Sensors (Switzerland)*, 20(1). doi: 10.3390/s20010303.

Vagenas, N., Runciman, N. and R.clément, S. (1997) 'A methodology for maintenance analysis of mining equipment', *International Journal of Surface Mining, Reclamation and Environment*, 11(1), pp. 33–40. doi: 10.1080/09208119708944053.

Vatn, J., Hokstad, P. and Bodsberg, L. (1996) 'An overall model for maintenance optimization', *Reliability Engineering and System Safety*, 51(3), pp. 241–257. doi: 10.1016/0951-8320(95)00055-0.

Velmurugan, R.S, Dhingra, T. (2015) 'Maintenance strategy selection and its impact in maintenance function', *International Journal of Operations and Production Management*, 35(12), pp. 1622–1661. doi: 10.1108/MIP-05-2017-0088.

Vilarinho, S., Lopes, I. and Oliveira, J. A. (2017) 'Preventive Maintenance Decisions through

Maintenance Optimization Models: A Case Study', *Procedia Manufacturing*, 11(June), pp. 1170–1177. doi: 10.1016/j.promfg.2017.07.241.

Vlok PJ (2011) 'No Tit', *Introduction to practical statistical analysis of failure time data: Long term cost optimization and residual life estimation. Course notes*.

Vos, A., Strydom, H. and Delport, C. (2012) *Research at Grass Roots*. 4th Editio. Van Schaik Publishers.

Waeyenbergh, G. and Pintelon, L. (2002) 'A framework for maintenance concept development', *International Journal of Production Economics*, 77(3), pp. 299–313. doi: 10.1016/S0925-5273(01)00156-6.

Walters, J. (2008) 'Overview of public transport policy developments in South Africa', *Research in Transportation Economics*, 22(1), pp. 98–108. doi: 10.1016/j.retrec.2008.05.023.

Weston, P. (2015) 'Perspectives on railway track geometry condition monitoring from in-service railway vehicles', *Vehicle System Dynamics*, 53(7), pp. 1063–1091. doi: 10.1080/00423114.2015.1034730.

Wijesinghe, D. and Mallawarachchi, H. (2019) 'A systematic approach for maintenance performance measurement: Apparel industry in Sri Lanka', *Journal of Quality in Maintenance Engineering*, 25(1), pp. 41–53. doi: 10.1108/JQME-03-2017-0022.

Wilson, R. (2010) 'Essentials of Business Research: a guide to doing your research project', *Sage*.

Yin, R. (2009) *Case study research: Design and methods, Case Study Research: Design and Methods*. doi: 10.1016/S0022-3913(12)00047-9.

Zhang, Y.. (2017) 'Optimal sustainable life cycle maintenance strategies for port infrastructures', *Journal of Cleaner Production*. Elsevier Ltd, 142, pp. 1693–1709. doi: 10.1016/j.jclepro.2016.11.120.

Zilka, M. (2014) 'Methodology for Selecting the Appropriate', *Maintenance systems*, pp. 209–216.

APPENDIX A: RESEARCH STRATEGIES

Research strategy	Principal orientation	Advantages/disadvantages
Qualitative research	Words and description	-Flexible investigation -Interaction with participants -informative as clarification can be easily sought if need be -Outlines the participants' viewpoints - The researcher can give participants the context. This helps in ensuring participants fully understand research at hand
Quantitative research	Numbers and measurement	-Structured data collection -Normally no interaction between the researcher and the participants -Hard, reliable data -Outlines the researcher's viewpoint -A generalisation of the population
Mixed methods research	Combination of qualitative and quantitative research methods within a single study	- Using both quantitative and qualitative research strategies may allow the researcher to capitalise on the strengths and eliminate/reduce the demerits of each method -Mixed methods enable the researcher to simultaneously address a range of confirmatory and exploratory questions with both the qualitative and quantitative approaches, therefore, verify and generate theory in the same study -It provides strengths that offset the weaknesses of both quantitative and qualitative research and therefore has the potential to provide better (stronger) inferences -Mixed methods research encourages the use of multiple world views or paradigms rather than the typical association of certain paradigms for quantitative researchers and others for qualitative researchers

APPENDIX B: CLASSIFICATION OF STUDIES BY THE TYPE OF PUBLICATION

Type of publication	Number
Magazine of Civil engineering	1
Sensors	2
Non-ferrous metals	1
IEEE International Conference on industrial engineering and Engineering Management	1
IEEE Vehicle power and propulsion	1
Operations and Production Management	6
Quality in Maintenance Engineering	37
Records Management	1
AIP conference proceedings	1
Engineering structure	1
Renewable and Sustainable Energy Review	1
Applied Energy	1
IFAV Papers Online	1
Materials Science and Engineering	1
Measuring business excellence	1
Business Process Management	1
Productivity and performance management	3
Quality in maintenance management	2
Business Economics and management	1
Rural of electrical power conference	1
IFIP advance in information and communication technology	1
International Conference on	1
IEE Transistor dielectrics and electrical insulators	1
Measurement and science and technology	1
IEEE symposium in computer application	1
Quality and Reliability engineering	1
Reliability and systematic maintenance	1
Production research	1
Systems assurance engineering and	1

Statistical planning and inference	1
Total studies for systematic review	75

APPENDIX C: FRAMEWORK VALIDATION PRE-READ DOCUMENT

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Maintenance strategy implementation framework validation

Pre-read document

Authored by: Meluleki Bhebhe

Study leader: Mr P N Zincume

Foreword

This document serves as a pre-read material necessary for validation. The document provides an understanding of the maintenance strategy implementation framework developed for the Passenger Rail Agency of South Africa (PRASA). An overview of the background of the study, the methodology and a summary of the study's literature is provided. Consequently, the maintenance strategy implementation framework is given.

Introduction

This section aims to provide an overview of the research inquiry by summarizing the background, research question, research aim, and the research design and methodology in developing the product categorization framework.

1.1 Background

South Africa faces a multitude of challenges in public transport services such as affordability, availability and safety. Passenger Rail Agency of South Africa has a market share of over 13% and transport over 372 million people to places of employment and education on an annual basis. According to Prasa cooperate plan, (2019/21) one of the values of the organisation is to provide services that meet or exceed customer satisfaction. In doing so the organisation has to ensure the availability of its trains is high. However, at this time as stated by the 2019/21 corporate plan, the performance and service offering is at an all-time low. This, therefore, means service is poor, unreliable, unpredictable and unsafe resulting in the decline of customer and stakeholder confidence of PRASA’s capability to deliver its mandate.

In the past years, the performance of Prasa declined significantly from 646 million passenger trips recorded in 2009 to 472 million by 2012 which translates to 174 million drop which is 26,9% drop in the number of passenger trips. Besides this significant drop in passenger train trips, PRASA, as stated by the cooperate plan, is struggling with train delays and cancellations.

The corporate plan 2019/21 states that 1827 coaches are out of service or 40% of the fleet not in service- 62% of this is in maintenance (own and contractors). A high percentage of coaches out of service (62%) is due to maintenance, as such this research will focus on maintenance strategies to reduce the percentage.

1.2 Research Aim

This research inquiry aims to contribute towards improving the maintenance strategy at the Passenger Rail Agency of South Africa by proposing a suitable framework for the implementation of maintenance strategy.

1.3 Methodology of the research

For the study, a mixed-method research approach was employed where secondary quantified data sources on the maintenance strategies, maintenance strategy selection, maintenance strategy optimisation and maintenance performance measurement were utilized to determine and define the research problem.

1.4 The aim of this phase

The objective is to review and validate maintenance concepts identified, the categorisation of the concepts, the interaction of concepts and the framework's construct itself. This is accomplished by getting feedback from subject matter experts (SMEs) on the framework. Consequently, based on the feedback received from the SMEs, necessary iterations and/or improvements will be made to develop a final product categorization framework.

1.5 Identified maintenance conceptual concepts

The literature review was conducted to identify different maintenance tasks/ activities/maintenance strategy elements/maintenance strategy components, criteria in deciding which maintenance tasks to perform and when they should be done and maintenance objectives. These were then termed by the researcher to be maintenance concepts. A total of 61 maintenance concepts were identified. These are availability, reliability, reduction of unexpected failures, reduction of downtime, customer safety, quality service, protection of environment, level of technical skill needed, number of maintenance personnel needed, continuous technical and interpersonal training of maintenance personnel, CMMS, communication, management commitment, reporting, failure effect, benchmarking, failure rate, failure mode, stock tracking, equipment technical condition, monitoring, legislation and rules, historical data collection and processing, age of equipment, operating time, work order, flow of information, measuring, testing, servicing, overhauling, inspecting, replacing, repairing, cleaning, tightening, lubricating, adjustment, coordination, recording, grouping of components, level of maintenance needed, procurement, time allocation, allocation of resources, frequency of maintenance, allocation of maintenance tasks, coordination, formation of maintenance teams, determining maintenance actions, contracting scheduling maintenance procedure, spare parts management, inventory cost, labour cost and tools.

1.5.1 Categorisation of concepts

The identified concepts were then grouped into 8 categories as shown in Table 1 below.

Table 1 Concept categories

Objectives	**Personnel**
Availability, Reliability, Reduction of unexpected failures, Reduction of downtime, Customer safety, Quality service, Protection of environment	Level of technical skill needed, Number of maintenance personnel needed, Continuous technical and interpersonal training of maintenance personnel, Communication

	Management commitment
Data acquisition and analysis Reporting, Failure effect, Benchmarking, Failure rate, Failure mode, Stock tracking, Equipment technical condition, Monitoring, Legislation and rules, Historical data collection and processing, Age of equipment, Operating time, Work order, Flow of information, CMMS	**Materials requirements** Spare parts management, Inventory cost, Labour cost, Tools
Planning Grouping of components, Level of maintenance needed, Procurement, Time allocation, Allocation of resources, Frequency of maintenance, Allocation of maintenance tasks, Coordination, Formation of maintenance teams, Determining maintenance actions, Contracting	**Execution** Measuring, Testing, Servicing, Overhauling, Inspecting, Replacing, Repairing, Cleaning, Tightening, Lubricating, Adjustment, Coordination, Recording
Maintenance program Maintenance procedure Benchmarking	**Scheduling** Scheduling

1.5.2 Interaction of categories

As shown in Section 1.5.1, concepts were grouped into different categories. Figure below shows how these different categories interact with each other. The interaction gives a full picture of the maintenance process in the rail environment.

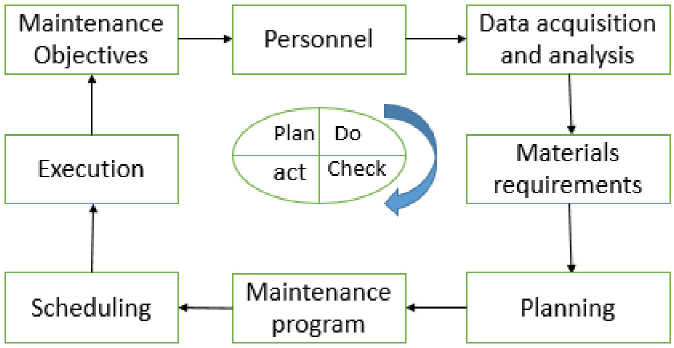


Figure 1 Interaction of categories

The maintenance process will start with the organisation spelling out their maintenance objectives. This helps the organisation to focus on what is important to the organisation and is in line with the business objective. In the rail environment, reliability, availability, care for the environment should be of concern. These maintenance objectives help to identify the kind of personnel needed in the maintenance department hence as depicted by Figure 1, it is followed by personnel.

Personnel identified should be having technical skills to enable the organisation to meet the maintenance objectives. Based on the need to strive for excellence all the time, personnel much be continuously trained.

When the personnel to perform different duties has been identified, the equipment of the organisation is assessed through inspection, historical data or any other method to determine the necessary tasks that need to be performed. The full determination of what needs to be done helps in identifying the kind of material needed and its quantity.

Material requirements are determined by the condition of the equipment. Tools and spare parts needed to restore the equipment to operation. Material quantity is easy to establish as on data acquisition and analysis, inventory levels would have been identified, therefore the difference from what is needed would need to be purchased.

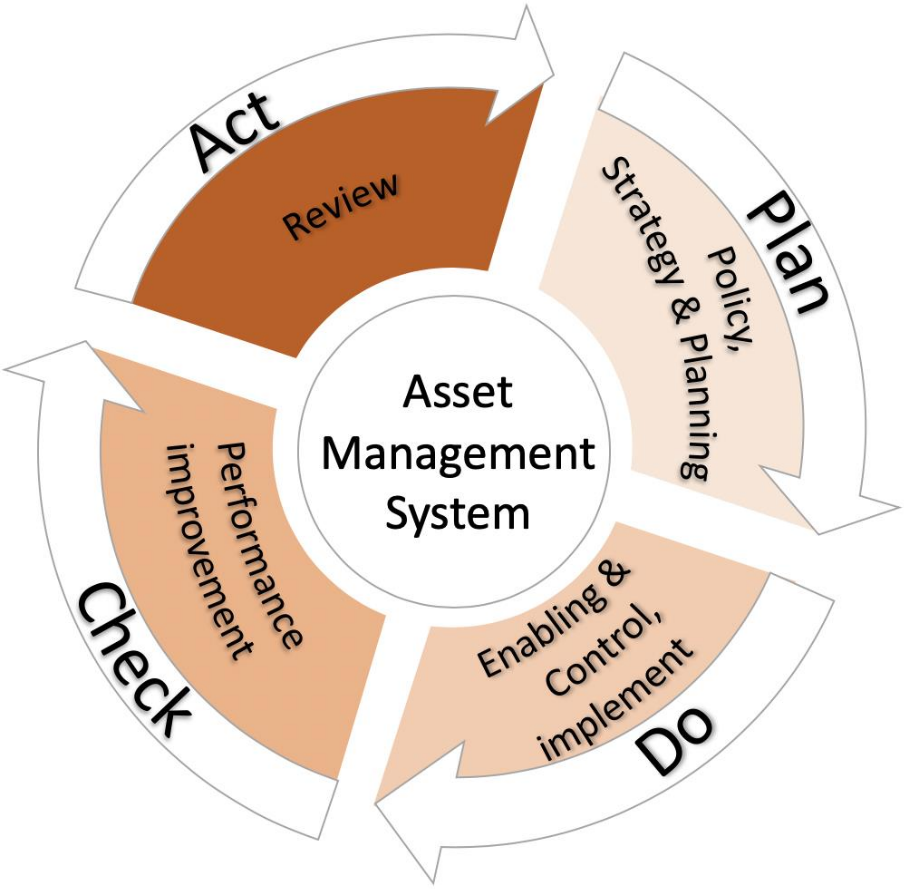
Personnel, data acquisition and analysis and materials requirements can be grouped into resource requirements. Hence, as such, when resource requirements have been established, planning for maintenance needs to take place. At this stage, maintenance teams are formed based on the personnel available, tasks to be performed and the objectives of carrying out those tasks.

Maintenance program specifies the level of maintenance that needs to be undertaken and when it should be done. This phase also specifies the maintenance procedure. This helps to establish a standardised way of doing things. Standardisation improves maintenance task control and helps in improving the quality of maintenance.

When the maintenance program has been established, scheduling has to be done. Scheduling aims to bring together everything that is needed, such as resources (spare parts, tools, personnel, equipment) to the right place.

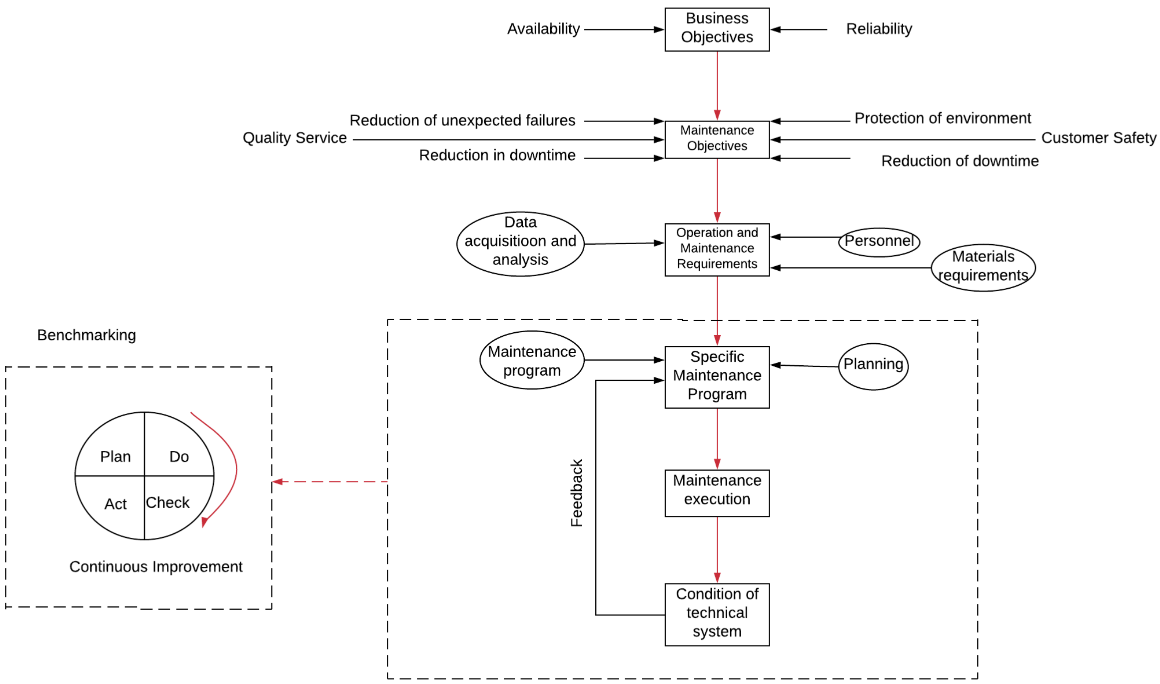
Upon bringing all things to the right places, the execution of maintenance tasks has to be undertaken. These include cleaning, lubricating, repairing, replacement depending on the level of maintenance established through the maintenance program.

The maintenance process is evolutionary, it follows the PDCA principle (Plan-Do-Check-Act). It is the process of continuous improvement. The PDCA aligns with the ISO55000 Asset Management Standard.



1.6 Developed framework

The developed framework synchronised all the concepts identified in Section 1.5.



The framework starts with the business objectives which are then translated into maintenance objectives. It helps to bridge the gap between business strategy and maintenance strategy. This leads to an effective formulation of a maintenance strategy (Kelly, 2006; Pintelon and Parodi-herz, 2008; Silonen, 2011).

The maintenance objectives lead to operation and maintenance requirements. This stage consists of tactical and operational planning (Pintelon LM, 1992). Maintenance strategy elements such as materials requirements, personnel and data acquisition and analysis are then included(M. C. Eti, Ogaji and Probert, 2006a, 2006b; Mark C. Eti, Ogaji and Probert, 2006).

1.7 Conclusion

Based on an extensive review of the maintenance literature from different environments and world-wide railway sector, an approach (framework) for a maintenance strategy has been developed. It has been developed to make maintenance in the rail environment a more proactive approach. In conducting the literature review maintenance tasks/ activities, objectives, criteria for selecting maintenance actions and when they should be performed were identified for the formulation of a maintenance strategy framework.

The framework regards business objectives, regulations, health, safety and environment demands and interaction between different maintenance tasks. The maintenance strategy framework possible phases of activities, such as; objectives, personnel, scheduling, data acquisition and analysis, materials requirements, maintenance program and maintenance plan, and execution of maintenance tasks and continuous improvement of a maintenance process are given.

APPENDIX D: INTERVIEWEE BACKGROUND SUMMARY FOR SME INPUT ANALYSIS

Sector	Participant (P)	Background/occupation	Reason for inclusion
Rail environment	P1	Acting Engineering Services Manager, Registered engineer, Project management experience, Former Prasa head of electrical department	8 years of experience in the rail environment, Experience in fault finding techniques and maintenance management, Involved in reliability and safety research in the rail environment, Involved in staff development programs, Involved in drawing up maintenance plans
Rail environment	P2	Electrical fitter (2004 to 2009), Senior technical training officer (2009 to present), Training apprentices and adult learners on upgrades and new technology, training for New X'tropolis to replace old rolling stock	Worked in the rail environment for 16 years, Have experience in maintenance in the rail environment
Rail environment	P3	Since 2014 maintenance, Maintenance operations management	Expertise in rolling stock maintenance, Knowledge in human resource development

Rail environment	P4	Electrical engineer by profession, has been working in maintenance for the past 18 years with 12 years in Metrorail, former senior engineering technician, former chief technician, former acting maintenance engineering manager, currently Systems engineer	Expertise in maintenance, expertise in rolling stock maintenance, expertise Metrorail maintenance management, involved in maintenance projects, involved in maintenance troubleshooting
Rail environment	P5	Degree in mechanical engineering, Master of Engineering Management, practised as a mechanical engineer for 3 years, a field support engineer for almost 2 years, Prasa engineering manager from 2014 to current, enrolled as a masters student in business administration at Regent University.	Experience in maintenance operations and project management, responsible at Prasa for maintenance of rolling assets in totality including engineering, operations and planning activities
Rail environment	P6	Production manager in the rail environment	Responsible for budget requirements, forecasting of material, maintenance activities of rolling stock, planning and controlling

			component repair and overhaul for general overhaul program

APPENDIX E: SME INPUT ANALYSIS QUESTIONS

Aspect	No	Question
Identification of concepts	1	Do you think the identified concepts are relevant for maintenance?
	2	Do you think the concepts were properly identified?
	3	Do you think all concepts needed in performing maintenance were identified?
Concept categories	4	Do you think the concepts were properly categorised?
	5	Do you think all the categories necessary were identified?
	6	Do you think other categories should be added?
Interaction between categories	7	Do you think the flow of maintenance has been properly represented in the interaction of concept categories?
	8	Do the categories interact as shown?
	9	Do you think that necessary changes that can be made?
Framework developed	10	Do you think the framework can be used for effectively implementing maintenance of rolling stock?
	11	Do you think the inclusion of the continuous improvement aspect is necessary?
	12	Are there any comments/additions/subtractions to the construct of the framework that you would like to make?